1   **Pyroclastic Flow Deposits on Venus as Indicators of Renewed Magmatic Activity**

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26 **MAJOR POINTS**

27 • **We map deposits on Venus formed by collapse of volcanic eruption columns.**

28 • **Radar properties suggest the deposits are made up of coarse clastic debris.**

29 • The radar-bright material is currently being eroded by Venus subareal processes.

30 • **We propose that these deposits mark sites of renewed magmatic activity.**

Abstract. Radar-bright deposits on Venus that have diffuse margins suggest eruptions that distribute debris over large areas due to ground-hugging flows from plume collapse. We examine deposits in Eastern Eistla, Western Eistla, Phoebe, and Dione Regiones using Magellan data and Earth-based radar maps. The radar-bright units have no marginal lobes or other features consistent with viscous flow. Their morphology, radar echo strength, polarization properties, and microwave emissivity are consistent with mantling deposits comprised of few-cm or larger clasts. This debris traveled downhill up to ~100 km on modest slopes, and blanketed lava flows and tectonic features to depths of tens of cm to a few meters over areas up to 40×10^3 km^2. There is evidence for ongoing removal and exhumation of previously buried terrain. A newly identified occurrence is associated with a ridge belt south of Ushas Mons. We also note radar-bright streaks of coarse material west of Rona Chasma that reflect the last traces of a deposit mobilized by winds from the formation of Mirabeau crater. If the radar-bright units originate by collapse of eruption columns, with coarse fragmental material entrained and fluidized by hot gases, then their extent suggests large erupted volatile (CO_2 or H_2O) amounts. We propose that these deposits reflect the early stage of renewed magmatic activity, with volatile-rich, disrupted magma escaping through vents in fractured regions of the upper crust. Rapidly eroding under Venus surface conditions, or buried by subsequent eruptions, these markers of recently renewed activity have disappeared from older regions.

50   **INTRODUCTION**

51   Volcanic deposits dominate the landscape of Venus. At least three quarters of the

52   planet is comprised of smooth plains with volcanic dome fields, coronae, and shield

53   volcanoes. Most of these units are associated with morphologies such as lobate flow

54   fronts, channel and levee structures, and pit-like or linear vents. Their surface roughness,

55   as inferred from radar backscatter strength and polarization properties, is consistent with

56   that of Hawaiian basalts of the pahoehoe to a'a types [Campbell and Campbell, 1992].

57   With the exception of "pancake" domes and narrow channels (canali) of enormous

58   length, there are few features that have no obvious terrestrial parallel.

59   One type of deposit not explained by simple flow emplacement exhibits strong radar

60   echoes, diffuse margins, and a lack of internal lobes or channels. These features have

61   been identified on volcanoes in Dione Regio [Keddie and Head, 1995], on corona

62   margins in western Eistla Regio [Campbell and Clark, 2006], and surrounding hybrid

63   volcano-tectonic features near Sappho Patera in eastern Eistla Regio [McGill, 2000] (Fig.

64   1). All authors suggest some type of pyroclastic or ignimbritic process to explain their

65   distribution and radar scattering properties. A very different type of landform at Scathach

66   Fluctus, suggested to be an ignimbrite-like deposit by Ghail and Wilson [2013], has

67   distinct lobate margins more similar to those of lava flows than the diffuse margins of the

68   units studied here. To date, there has been no subsequent effort to examine the radar-

69   bright, diffuse-margined deposits as a group, search for additional occurrences, and

70   consider the implications of their stratigraphic position.

71   Work based on Venus Express VIRTIS data shows 1.02-μm emissivity enhancements

72   interpreted as evidence for recent (though of indeterminate age) eruptions [Smrekar et al.,

73   2010]. These sites include Hathor and Innini Montes, two of the Dione Regio volcanoes

74   noted as having radar-bright, diffuse-margin summit deposits. In contrast, Ushas Mons

75   has neither enhanced 1.02-μm emissivity nor radar-bright summit material. This

76   correlation suggests a potential role of the radar-bright terrain in creating the infrared

77   emissivity anomalies.

78   Radar measurements are the primary method of investigating the surface properties of

79   Venus. The data used here come from the Magellan orbital radar mission and Earth-based

80   radar mapping. Magellan collected near-global image coverage, in one sense of radar

81 polarization (horizontal transmit, horizontal receive), with about 100-m spatial resolution.

82 Between radar mapping bursts, Magellan measured the microwave thermal emission

83 from the surface, which is related to the dielectric permittivity and small-scale roughness

84 of the terrain [Pettengill et al., 1992; Campbell, 1994]. The spatial footprint of the

85 emissivity measurements is 20-30 km in the latitude range studied here, though the global

86 gridded dataset is resampled at a 4.6-km posting. The radar-bright units studied below

87 span at least two emissivity footprints along their N-S and E-W axes.

88 Earth-based radar mapping can achieve 1-2 km spatial resolution, and measure echoes

89 in both the opposite-sense (OC) circular polarization and the same-sense circular (SC)

90 mode. The OC echoes are very similar to Magellan measurements, and are strongly

91 modulated by slopes that face toward the radar. The SC echoes are much more sensitive

92 to small-scale surface roughness than to topographic slopes. We can also form the

93 circular polarization ratio (CPR=SC/OC), which allows for simple comparisons with

94 rough surfaces on the Earth. The utility of these data were demonstrated in mapping of

95 fine debris in the Venus highlands [Campbell et al., 2014; Whitten and Campbell, 2016],

96 and we now have co-registered coverage of the side of Venus that faces Earth at inferior

97 conjunction from 1988, 2012, and 2015 (the relevant part of which is shown in Fig. 2).

98 In this work, we further document the locations, physical properties, planform, and

99 stratigraphic position of radar-bright deposits with diffuse margins, using Magellan data

100 for high-resolution mapping and Earth-based data, where available, for polarimetric

101 analysis. These analyses are used to constrain the stratigraphy and spatial scale of

102 emplacement with respect to geologic setting. Finally, we discuss the implications of our

103 results for plume collapse models, recent and future studies of infrared surface emissivity,

104 and the inference of ongoing volcanic activity.

105

106 **LOCATIONS AND PROPERTIES OF RADAR BRIGHT UNITS**

107

108 *Eastern Eistla Regio*. Campbell and Clark [2006] noted occurrences of radar-bright

109 material with diffuse margins in eastern Eistla Regio, many on the western flank of

110 Pavlova Corona (units P1 to P3, Figs. 3-4). Two other nearby deposits are associated with

111 a densely ridged area (unit R1) and with an unnamed small corona southwest of Pavlova

112   (unit C1). The units have wispy or diffuse margins, moderate to very high backscatter

113   coefficients, and appear to cover pre-existing volcanic and tectonic features. In their

114   central regions there may be no distinguishable features, but closer to the margins the

115   outlines of buried lava flows, graben, or fractures emerge from a thinning cover. Similar

116   properties are associated with a unit on the southwest flank of Didilia Corona, and in each

117   case the radar-bright materials appear to have moved downhill from corona margins or

118   ridged terrain (Fig. 5). A topographic profile through Unit P3 shows that the bright

119   materials cover a distance of about 100 km over slopes no larger than ~0.3° (Fig. 6). The

120   total area covered by this single unit is about 7,600 km^2.

121   Two locales (northern unit P2 and southeastern unit D1) have prominent patterns of

122   radar-dark streaks, which we infer to be fine-grained material moved by the wind onto

123   the radar-bright materials [Greeley et al., 1992]. On unit D1, the dark material has moved

124   westward (the direction of the prevailing wind at the surface) from a 65-km diameter

125   volcanic edifice with a radar-dark summit region. The radar-bright unit covers the west

126   flank of this volcano, so the wind streaks must reflect ongoing aeolian mantling of unit

127   D1 (Fig. 5). It is interesting that such a small volcano summit region supplies the required

128   volume of streak material, perhaps implying a fine-grained, localized pyroclastic deposit.

129   In the case of northern unit P2, the streaks form a roughly radial pattern suggesting a

130   source to the north, but their orientation is nearly orthogonal to the prevailing wind (Fig.

131   7).

132   The most dramatic remote-sensing property of these units is their high radar

133   backscatter strength. Within Eastern and Western Eistla Regiones the deposits have

134   echoes stronger than any edifice-related lava flows: backscatter coefficient or "sigma-

135   zero" values at ~46° incidence angle are about -9 dB for unit P3. Such backscatter

136   coefficients imply either (1) rough terrain (expressed as either a continuous topographic

137   profile or a field of discrete objects) at the scale of the radar wavelength, or (2) an

138   enhanced Fresnel reflectivity due to an increase in the real permittivity of the materials.

139   The 12.6-cm wavelength, horizontal-polarized emissivity, E_{H}, for radar-bright units near

140   Pavlova and Didilia are 0.80 to 0.85 at incidence angles around 44°. These values

141   correspond to a dielectric permittivity, ε' , range of about 3 for a plane surface to about

142   6.5 (similar to bare rock) for a surface that is rough at the wavelength scale [Campbell,

143   1994]. Most of the bright units have slightly higher E_H values relative to the surrounding

144   flows, which is consistent with a higher degree of wavelength-scale roughness rather than

145   an increase in permittivity. For comparison, the mean emissivity value for Venus is

146   0.845, and high-elevation regions of Maxwell Montes have typical values of ~0.3 due to

147   surface-atmosphere chemical reactions [Pettengill et al., 1992].

148   Absent enhanced reflectivity, the high radar backscatter values must come from

149   significant roughness, expressed as the rms height/slope of either a continuous rough

150   profile or a field of discrete objects, on the 12.6-cm horizontal scale. The necessary rms

151   height/slope would be comparable to that of terrestrial a'a flows, or to a field of clasts

152   with diameters up to at least about 4 cm [Campbell, 2002]. The lack of any obvious

153   structure (at the few-hundred meter scale) within the deposits suggests a blanket of clastic

154   debris that is always the locally highest stratigraphic unit. The actual size-density

155   distribution of the clasts cannot be determined; there may be a sorting process during

156   emplacement that leaves larger rocks close to the vent or deposits them preferentially at

157   the base of a downslope deposit. The presence of wind streaks would suggest clast sizes

158   toward the smaller end of the range in those locales, since the fine-grained windblown

159   material would not easily cover more rugged terrain.

160

161   *Western Eistla Regio*. The two major hybrid volcano-tectonic constructs of Western

162   Eistla Regio, Anala Mons and Irnini Mons (with Sappho Patera at its summit), have

163   large, radar-bright deposits with diffuse margins emanating radially and extending

164   downslope from their corona-like, densely ridged annuli [McGill, 2000] (Figs. 8-9). A

165   profile through Unit I1 shows that the area of continuous bright material covers about 70

166   km from a point on the Irnini Mons flank, and extends onto nearly flat terrain to the north

167   (Fig. 10). The average slope of the Irnini flank in this area is 1.2°. The margins of units

168   I1, I2, and A1 are uncertain where they meet the densely fractured terrain, but there is

169   some evidence that diffuse deposits extend onto the floor of Sappho Patera. The contacts

170   between the floor units and the radar-bright terrain are poorly defined, and it is difficult to

171   determine whether there is embayment by the lava flows or exhumation of these flows by

172   erosion of the mantling debris. Very thin streaks, inferred here to form by aeolian

173   movement of fine material, on the radar-bright units, and subtle diffuse patterns

174   overlapping dark flows just inside the dense fracture belts are more consistent with the

175   latter scenario. A minimum area for the bright deposits around Anala (Units I1 and I2) is

176   about 41,000 km^2. Radar brightness (the average sigma-zero value for central unit I1 is -

177   9.7 dB at 45° incidence angle) and emissivity properties for unit I1 are similar to those

178   observed in Eastern Eistla Regio.

179   The northwestern portion of unit I1 shows that the mantling unit thickness must be a

180   few meters or more to cover flows with central channels as well as lobate margins high

181   enough to produce a glint from the radar-facing slope (Fig. 11). This view illustrates the

182   apparent erosion of the mantling material in the dense pattern of linear streaks, trending

183   north-northwest, and the patchy brighter areas on the radar-dark flow to the northwest.

184   There are also areas of darker radar signature within units I1 and I2. We infer that these

185   may be localized areas where the initial deposit was thin, which seems unlikely for a

186   surge deposit traveling such distances, or that subsequent breakdown of the coarse

187   material has begun to remove the mantle.

188   Unit I3 is anomalous among radar-bright deposits noted thus far (Fig. 12). It is situated

189   in a topographic low of a region characterized by both plains-forming (broad with

190   indistinct or non-lobate margins) and edifice-derived (narrow with lobate margins) flows

191   (Fig. 9). The deposit mantles tectonic fractures and ridges, as well as a moderate-

192   backscatter flow complex from the southwest. There is no evident direction of transport,

193   and the margins are a collection of linear "spines" that parallel the local tectonic fabric.

194   At no point along its margin does unit I3 appear to be embayed by a later flow. It also lies

195   just beyond the farthest extent of flows that emerge from the margin of unit I1, so we

196   cannot make a stratigraphic connection from that relationship. We suggest that I3 is an

197   erosional remnant of a once larger I1 deposit, perhaps protected to some degree by its

198   location in the lowest local topography. This would be consistent with the "spiny"

199   appearance that suggests formation (and perhaps aeolian removal) of fine material by

200   erosion of the original rocky mantle.

201   These observations confirm the inferences from Pavlova and Didilia Coronae that the

202   radar-bright, diffuse deposits are superposed on all other geologic features. Even more

203   than in those instances, the deposits at Irnini Mons suggest substantial removal of clastic

204   mantling material by breakdown of the rocks and redistribution of resulting fines by the

205   wind. While they are thus stratigraphically "young", the diffuse deposits have undergone

206   a considerable degree of weathering. The rate of that breakdown might be high under

207   Venus conditions [Fegley et al., 1997].

208

209   *Dione Regio.* Keddie and Head [1995] present a detailed analysis of volcanic

210   stratigraphy for the major edifices within Dione Regio (Figs. 1-2). They note radar-

211   bright, diffuse-margin material near the summits of Hathor and Innini Montes, and

212   perhaps on Nepthys Mons. Only near the summit of Innini Mons does the radar-bright

213   signature appear to arise in part from altitude dependent surface-atmosphere effects on

214   the dielectric permittivity. They further note that these materials blanket underlying

215   features, including lava flows and tectonic features such as graben, and infer a pyroclastic

216   or ignimbrite style of emplacement. Dione Regio is the only major location of radar-

217   bright, diffuse terrain within the Earth-based radar coverage (Fig. 2), and our combined

218   data from 1988, 2012, and 2015 offer a view of polarimetric scattering behaviors (Fig.

219   13) at a signal-to-noise ratio much higher than that available to Keddie and Head [1995].

220   We note multiple areas of radar-bright units with diffuse margins on Hathor and Innini

221   Montes, but nearby Ushas Mons appears to have no major instances of this type of

222   deposit (Fig. 13a). Those on Innini Mons are relatively concentric to the cluster of radar-

223   bright domes on the summit, while those on Hathor Mons extend away from an oval

224   summit region toward the north and west. We also note a large (maximum dimensions of

225   ~230 km on NW-SE axis, ~100 km SW-NE), radar-bright feature along the densely

226   fractured terrain south of Ushas Mons that appears to superpose the ridge structure and

227   some extensional features. This large radar-bright unit has not been previously discussed,

228   perhaps due to its location away from the major edifices and gaps in Magellan image

229   coverage.

230   Topographic profiles (Fig. 14) show that the radar-bright material south of Ushas

231   Mons extends ~70 km from a modest topographic high east of the ridge belt. In both

232   profiles the western extent of the deposit occurs near or within a local depression. The

233   local slope, dipping to the west, is only about 0.14^{o} along the northern transect, while the

234   southern transect has what might be (extrapolating through the data gap) up to about a

235   0.3^{o} slope at its eastern edge. The area of the bright deposit is about 21,000 km^{2}.

236   In both the Magellan image and the Earth-based SC data, the ridge-related material is
237   very bright (an average sigma-zero value of -10 dB at 33° incidence angle), suggesting a
238   high degree of surface roughness (Fig. 15). The circular polarization ratio, which is
239   sensitive to the degree of scattering by wavelength-scale roughness, shows enhanced
240   values for the radar-bright units on Hathor Mons and the ridge-belt area (Fig. 13b). The
241   deposits near the summit of Innini Mons are only modestly enhanced. The ridge-belt
242   feature and the bright deposit on the west flank of Hathor Mons have CPR values of 0.4
243   to 0.5 at incidence angles around 40°. These values are consistent with the upper range of
244   few-cm to decimeter-scale roughness for basaltic flows on the Earth [Campbell, 2009],
245   and stand out markedly against the background of lower CPR values for the plains- and
246   edifice-forming flows. As with the radar-bright deposits in Eistla Regio, there is no
247   evidence of the low microwave emissivity expected if these brightness changes came
248   from an increase in the Fresnel reflectivity.

249   Keddie and Head [1995] noted that Nepthys Mons, formed on the north flank of a
250   ridge belt, has a 40-km diameter region of enhanced radar echoes near its highest
251   elevation. The SC image shows an oblong region of enhanced echoes in the same region,
252   though the strength of this echo with respect to the surrounding flows is not as
253   distinguishing as those on Hathor Mons or the ridge belt south of Ushas Mons (Fig. 16).
254   Some parts of the radially fractured flanks of Mielikki Mons might be mantled by radar-
255   bright material, but the SC echo shows only modest enhancement across the whole
256   edifice (Fig. 17). Finally, one site noted in the VIRTIS study of Smrekar et al. [2010] but
257   not visible in the Earth-based coverage, Idunn Mons (Fig. 18), may have radar-bright,
258   diffuse material on the northwestern parts of its summit, but even at the full resolution of
259   the Magellan images we cannot confirm the mantling relationships evident in other
260   locales.

261

262   *Phoebe Regio*. Rona Chasma is part of the long rift zone of Phoebe Regio, trending
263   roughly SW-NE in our study locale (Fig. 19). Associated with the rift zone are numerous
264   volcanic flow fields. Centered on 0.5° S, 286° E is a field of radar-bright streaks
265   extending about 60 km along a SE-NW axis (Fig. 20). The streaks occur on a patch of
266   volcanic plains with very low radar backscatter that appears to be the oldest rift-related

267 flow unit superposing the regional plains. These very smooth flows are superposed by
268 radar bright (i.e., rougher) flow fields from fractures on the western side of Rona
269 Chasma. Where the radar-bright streaks meet the later flows, the margins of those flows
270 are less distinct than elsewhere, suggesting that the streak material has banked up against
271 the flow lobes. In at least one locale (noted on Fig. 20), a streak crosses over a flow and
272 causes an increase in the radar echo. This shows that the streaks form by redistribution of
273 coarse, clastic debris rather than by removal of a regolith cover to expose the rock
274 beneath [e.g., Greeley et al., 1992].

275 The streak materials appear to have traveled from NW to SE, which is not consistent
276 with the prevailing wind pattern. Even if they were oriented from east to west, it is
277 unlikely that the Venus surface winds can mobilize such large particles. A plausible
278 scenario is that these streaks formed as a result of winds associated with the formation of
279 the 23.8-km diameter crater Mirabeau (Fig. 19). The center of Mirabeau (1.1 N, 284.3 E)
280 is about 260 km from the farthest extent of the streaks, which trend nearly radial to the
281 crater. Figure 21 presents the likely sequence of events in this region, with the inference
282 that the streaks are the remnants of a once-contiguous deposit that may have extended
283 eastward to the fractures of Rona Chasma.

284

285 **DISCUSSION AND IMPLICATIONS**

286 The existence of radar-bright deposits with diffuse margins in a few locations on
287 Venus has been known since initial mapping efforts [Keddie and Head, 1995; McGill,
288 2000; Campbell and Clark, 2006]. Our work shows that these deposits comprise
289 moderate-scale units along fractures near the summits of classic shield volcanoes like
290 Hathor and Nepthys Montes, and perhaps Mielikki and Idunn Montes. Similar deposits
291 are related to densely fractured terrain south of Ushas Mons, the flanks of Pavlova and
292 Didilia Coronae, and surrounding the hybrid volcano-tectonic features Anala and Irnini
293 Montes. The radar-bright streaks near Rona Chasma may likewise have once extended to
294 the outer fractures of this rift zone.

295 In the larger occurrences, we find evidence for mantling of pre-existing lava flows and
296 tectonic features by clastic debris up to several meters thick, which thins and perhaps is
297 sorted to finer particle sizes downslope of the highest elevations. We also note evidence

298 for erosion of this material, exhumation of flow features, and isolated outliers that implies

299 larger initial extents. The smaller occurrences exhibit some of these attributes, but often

300 have less enhanced SC radar echoes; we speculate that these deposits are older, or were

301 not as initially extensive or thick, such that subsequent erosion has left less distinct traces.

302 In most cases there is no clear evidence for embayment of the mantling deposits by later

303 flows, so they are the locally youngest units except for radar-dark wind-streak material.

304 Only near Rona Chasma do we infer significant superposition of radar-bright, clastic

305 material by lava flows, and here the debris is confined to streaks aligned with winds from

306 the Mirabeau impact.

307 These deposits of clastic material are clearly ephemeral, since they are typically

308 observed only at the top of the local stratigraphy rather than interleaved with the flows

309 that make up the other deposits from the ridge belts or volcano summits. The bright

310 streaks west of Rona Chasma are a rare glimpse of an older deposit preserved on early

311 flows from the major regional source, and the total amount of material is small with

312 respect to the inferred initial coverage. We conclude that the clastic debris is most often a

313 recent volcanic phenomenon in each area, where the "recent" term can only have a

314 quantitative meaning if the rate of erosion is known.

315 Smrekar et al. [2010] modeled the surface emissivity at 1.02 μm from VIRTIS data

316 and Magellan topography, and found some degree of enhancement from Idunn, Meilikki,

317 Hathor, and Innini Montes; no such signature was noted for Ushas Mons. The first-order

318 correlation with the enhanced backscatter signatures might suggest that the radar-bright

319 material plays a role, perhaps due to grain size or compositional properties, in modulating

320 the 1.02 μm emissivity. An issue with this interpretation is that the modeled emissivity

321 (Fig 2B of Smrekar et al. [2010]) does not suggest enhancement from the large radar-

322 bright unit on the ridge belt south of Ushas Mons. If the radar-bright units are of

323 generally similar composition and particle size, then the lack of correlation in 1.02-μm

324 properties between the Hathor Mons summit and the ridge-belt unit suggests little

325 sensitivity of the modeled emissivity to these youngest materials.

326 It is unlikely that, given the density of the lower atmosphere, that fallout from a lofted

327 plume could emplace such extensive, clastic deposits [Fagents and Wilson, 1995; Wilson

328 and Head, 1981; Carter et al., 2006]. A more plausible mechanism for significant (10s of

329 km) lateral transport, especially of coarse particles, is plume collapse, where a low (up to

330 a few km), volatile-driven column creates an outer ring of cooler material falling away

331 from the peak rise altitude [Thornhill, 1993; Campbell et al., 1998; Glaze, 1999]. A linear

332 chain of vents on Venus would be even more effective than circular vents, for the same

333 eruption rates, in producing such collapsing columns, and thus pyroclastic flows [Glaze et

334 al., 2011]. This mechanism is also more consistent with the asymmetric distribution of

335 mantling material downhill of its sources at volcano summits or in the densely fractured

336 terrain. At the Magellan image resolution of ~100 m, we cannot further pursue

337 characterization of the possible vent geometries.

338 If our interpretation of a generally thin mantling layer of coarse debris is correct, then

339 the closest terrestrial comparisons are low aspect ratio features like the Taupo ignimbrite

340 (dated to ~186 CE). From a strictly morphologic perspective, the parallels with the large

341 radar-bright unit south of Ushas Mons are striking. Total range from the vent for the

342 Taupo deposit is ~80 km, the volume is about 30 km^3 over an area of about 20,000 km^2,

343 and there is few-cm scale clastic debris [Wilson, 1985; Dade and Huppert, 1996]. The

344 Venus example covers around 21,000 km^2, extends 70-100 km, has inferred thickness as

345 little as 10's of cm to a meter (i.e., a volume of 21 km^3 for a constant 1-m depth), and is

346 characterized by clast sizes of perhaps a few cm.

347 Highly silicic eruptions like Taupo are not expected on Venus based on existing

348 compositional data. There is evidence, however, of terrestrial basaltic eruptions that

349 produce deposits of similar morphology. Two such units were identified by Williams

350 [1983], with the larger covering an area of 1200 km^2. The dense, hot atmosphere of

351 Venus may create significant differences in how clasts are entrained and transported,

352 allowing emplacement over greater distances. Large explosive eruptions have also been

353 linked with the Columbia River Basalt province [Brown et al., 2014], supported by

354 models of volatile accumulation and explosive events in such ancient flood basalt

355 eruptions [Glaze et al., 2017].

356 Even the smaller units mapped here, assuming they were originally up to a few meters

357 thick, imply a substantial total mass of volatiles (concentrations of up to 5% H_2O or CO_2)

358 in the rising magma [Airey et al., 2015], and a chain of vents extending along the

359 fractured terrain [Glaze et al., 2011]. In general, discharges of volatile-rich magma occur

360 during the early phases of a magma source's interaction with the surface. For example,

361 fire-fountain activity was typical of the early stages of lunar mare volcanism. Subsequent

362 eruptions were depleted of volatiles, yielding the more classic plains-forming lava flows.

363 Due to this timing the largest surviving lunar pyroclastic deposits occur only in elevated

364 regions (such as the Aristarchus Plateau) where the later flows did not cover them [Zisk

365 et al., 1977].

366 Venus has a much more active cycle of magmatic activity, with the expectation of

367 many batches of magma rising to the surface in any one region over time. Given their

368 stratigraphic position and requirement for enhanced volatile content, the radar-bright

369 clastic deposits may reflect the early phases of renewed magmatic activity. All of the

370 occurrences are related to elevated, fractured terrain within regions of extensive

371 volcanism, consistent with such new batches of magma contributing to uplift and

372 extensional tectonism in an area. There is evidence for erosion and removal of the coarse-

373 grained debris (perhaps quite rapid), so those we observe are only the thickest or

374 youngest deposits. There may have been many more such deposits over time, each

375 marking sites of renewed eruptive phases.

376

377 **CONCLUSIONS**

378 We examine radar-bright deposits with diffuse margins in Eastern Eistla, Western

379 Eistla, Phoebe, and Dione Regiones using Magellan data and Earth-based radar maps.

380 The radar-bright units have no marginal lobes or other features consistent with viscous

381 flow. Their morphology, radar echo strength, polarization properties, and microwave

382 emissivity are consistent with extensive mantling deposits comprised of few-cm scale

383 clasts. This coarse debris traveled downhill up to about 100 km on modest slopes, and

384 blanketed pre-existing lava flows and tectonic features to depths of 10's of cm to perhaps

385 a few meters. The coarse material thins with downhill distance from the highest

386 elevations, and there is evidence for ongoing removal and exhumation of previously

387 buried terrain. A newly identified occurrence lies astride a ridge belt south of Ushas

388 Mons, mirroring a similar correspondence with densely fractured terrain in Eistla Regio.

389 We also note radar-bright streaks of coarse material on lava flows west of Rona Chasma,

390 and suggest that these reflect the last traces of an earlier, more extensive deposit that was

mobilized by winds from the formation of Mirabeau crater. If the radar-bright units originate by collapse of eruption columns, with coarse fragmental material entrained and fluidized by hot gases, then their extent and volume suggests large erupted volatile (CO_2 or H_2O) amounts. We propose that these deposits reflect the early stage of recently renewed magmatic activity that supplies the volatiles and contributes to uplift and extensional tectonism in an area. Rapidly eroding under Venus surface conditions, or buried by subsequent volatile-poor eruptions, these markers of renewed activity have largely disappeared from older regions. Their short erosional timescale may offer new insights on surface chemical and aeolian processes. Future Earth-based observations and orbital missions could target these sites for evidence of crustal deformation or active eruptions. Future landed missions could better constrain the overall range of Venus surface composition as a guide to the volatile budget and physical properties of erupted material.

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493

494 **Fig. 1.** A Magellan left-looking radar map labeled with locations of features noted in
495 this study (approximate area 48 S to 25 N latitude, -85.5 E to 55 E longitude).
496

497 **Fig. 2.** Earth-based radar data summed from observations of the southern
498 hemisphere in 1988, 2012, and 2015. Opposite-sense polarization (OCP) radar
499 echoes, so echoes from areas closer to the center of the planet are much brighter.
500 Approximate area 48 S to 11 S latitude, -85.5 E to -11 E longitude. Blurred region at
501 upper left is due to radar echoes from Beta Regio that are "folded over" by the delay-
502 Doppler imaging method.
503

504 **Fig. 3.** Regional (10.8N–16.0N; 35.3E–40.0E) view of radar bright deposits (outlined
505 in orange) in the vicinity of Pavlova Corona. Magellan left-looking radar image data.
506 Black line denotes trace of topographic profile in Fig. 5.
507

508 **Fig. 4.** Three-dimensional perspective view of the region shown in Fig. 3, based on
509 Magellan image and altimetry data. View is from the south. Note downslope
510 emplacement of labeled units away from corona rims and densely ridged terrain.
511

512 **Fig. 5**. View of the southwest flank of Didilia Corona, with a radar-bright, diffuse unit
513 labeled D1; unit P2 from Fig. 3 is visible at lower right. Magellan left-looking radar
514 image data, image area 15.5N-17.6N, 35.8E-38.4E. Note the pattern of dark streaks
515 running west from the 65-km volcanic edifice at right center.
516

517 **Fig. 6.** Topographic profile of the southwest flank of Pavlova Corona, from 12.87 N,
518 36.79 E (left) to 13.90 N, 38.30 E (right). Vertical offset is in km from a reference
519 radius of 6051 km. The radar-bright material of Unit P3 covers approximately 100
520 km from the corona rim. Data are from the Magellan GTDR dataset. Raw along-track
521 footprint values are smoothed and gridded at a horizontal posting of 4.6 km. Vertical
522 accuracy can be as fine as about 20 m over smooth terrain.
523

524 **Fig. 7.** Full resolution, Magellan left-looking radar view of wind streaks in northern
525 part of radar-bright, diffuse unit P2 (lower left). Image width about 25 km; north at
526 top. Note the outlines of lava flows emerging from the northwestern margin of the
527 radar-bright deposit.
528

529 **Fig. 8.** Regional (9N–18N; 10E–22E) view of radar bright deposits (outlined in
530 orange) on Irnini and Anala Montes. Magellan left-looking radar image data.
531

532 **Fig. 9.** Three-dimensional perspective view of the region shown in Fig. 8 based on
533 Magellan image and altimetry data. View is from the north. Note downslope
534 emplacement of units I1, I2, and A1 away from densely lineated rims. Unit I3 is
535 isolated in the nearby plains.
536

537 **Fig. 10.** Topographic profile of the northern flank of Irnini Mons at 15.1 E longitude,
538 running from 16.92 N at left to 14.70 N at right. Vertical offset is in km from a
539 reference radius of 6051 km. The radar-bright material in this locale covers

540 approximately 70 km of the flank and adjacent flat terrain, but in other areas the
541 deposit extends to 80-100 km. Data are from the Magellan GTDR dataset. Raw along-
542 track footprint values are smoothed and gridded at a horizontal posting of 4.6 km.
543 Vertical accuracy can be as fine as about 20 m over smooth terrain.
544
545 **Fig. 11.** Full-resolution, left-looking Magellan image of radar-bright, diffuse deposit
546 northwest of Irnini Mons. Image width 188 km; north at top. Note the lobate flows
547 that disappear southwards beneath the bright mantling unit (northern part of unit
548 I1), and the dense streaks and residual patches that suggest ongoing erosion of the
549 mantle and exhumation of the flows.
550
551 **Fig. 12.** Full-resolution, Magellan left-looking radar image of unit I3. Image width
552 120 km; north at top.
553
554 **Fig. 13a.** Earth-based opposite-sense circular (OC) radar image of Dione Regio
555 [approximately 20.5 to 45 S latitude, 316 to 335 E longitude]; simple cylindrical
556 projection. White arrows denote locations of radar-bright, diffuse deposits.
557
558 **Fig. 13b.** CPR color overlay on OC image of the same region shown in Fig. 11a. Note
559 that CPR values in the ridge-belt region at center and some parts of the Hathor Mons
560 deposits are 0.4 to 0.5, suggesting high few-cm scale roughness.
561
562 **Fig. 14a.** Magellan left-looking radar image of the radar-bright material south of
563 Ushas Mons: area covered is 33 S to 28 S, 321 E to 326 E. White lines indicate
564 locations of topographic transects in Fig. 14b. Gaps are due to missing data in the
565 Magellan coverage.
566
567 **Fig. 14b.** Topographic profiles across the radar bright material south of Ushas
568 Mons: (1) at 30.35 N, running from 321 E at left to 326 E at right; (2) at 31.04 N,
569 running from 321 E at left to 326 E at right. Vertical offset is in km from a reference
570 radius of 6051 km; profile (1) is offset by an additional 500 m for clarity. The radar-
571 bright material covers ~70 km downhill of a topographic high just east of the ridged
572 terrain. Data are from the Magellan GTDR dataset. Raw along-track footprint values
573 are smoothed and gridded at a horizontal posting of 4.6 km. Vertical accuracy can be
574 as fine as about 20 m over smooth terrain. Gaps are due to missing data in the
575 Magellan coverage.
576
577 **Fig. 15.** Magellan left-looking radar image (top panel) of radar-bright materials
578 astride a ridge belt south of Ushas Mons; (lower panel) Earth-based SC polarization
579 image. Region shown is approximately 32.3 S to 28.6 S latitude, 322 E to 325.6 E
580 longitude.
581
582 **Fig. 16.** Magellan radar image (top panel) of Nepthys Mons at center right, with
583 Arecibo SC-polarization image (lower panel). Region shown is approximately 35 S to
584 31 S latitude, 313.5 E to 321 E longitude. Image width 780 km.
585

Fig. 17. Magellan left-looking radar image of Mielikki Mons, with Arecibo SC-polarization image of surrounding region as inset. Image width 422 km.

Fig. 18. Magellan left-looking radar image of Idunn Mons. Image width 195 km.

Fig. 19. Regional view from Magellan radar data of Rona Chasma and Mirabeau crater (23 km diameter). Image area approximately 1.7 S to 2.5 N latitude, 284 to 290 E longitude. Arrow notes region of radar-bright streaks on smooth plains unit.

Fig. 20. Magellan radar view of radar-bright streaks west of Rona Chasma. Image width 190 km. Black arrow notes location of brighter echo from lava flows where a streak crosses the lobe.

Fig. 21. Sketch maps showing the inferred sequence of geologic events west of Rona Chasma. (A) A smooth, radar-dark flow unit (black) from fractures along Rona Chasma floods a region of regional plains. (B) A deposit of clastic material (yellow) from the Rona Chasma fractures is emplaced on the smooth flows. (C) Rougher lava flows (red) superpose part of the clastic deposit, which is also eroding from its initial thickness and extent. (D) Mirabeau crater forms, and the resulting winds redeposit the remaining clastic material into streaks that bank against, and sometimes cross, the radar-bright lava flows.

Figure 1.

Didilia
Corona

Irnini
Mons

Anala
Mons

Pavlova
Corona

Ushas
Mons

Nepthys
Mons

Innini
Mons

Mielikki
Mons

Hathor
Mons

Figure 2.

Mielikki
Mons

Ushas
Mons

Nepthys
Mons

Innini
Mons

Hathor
Mons
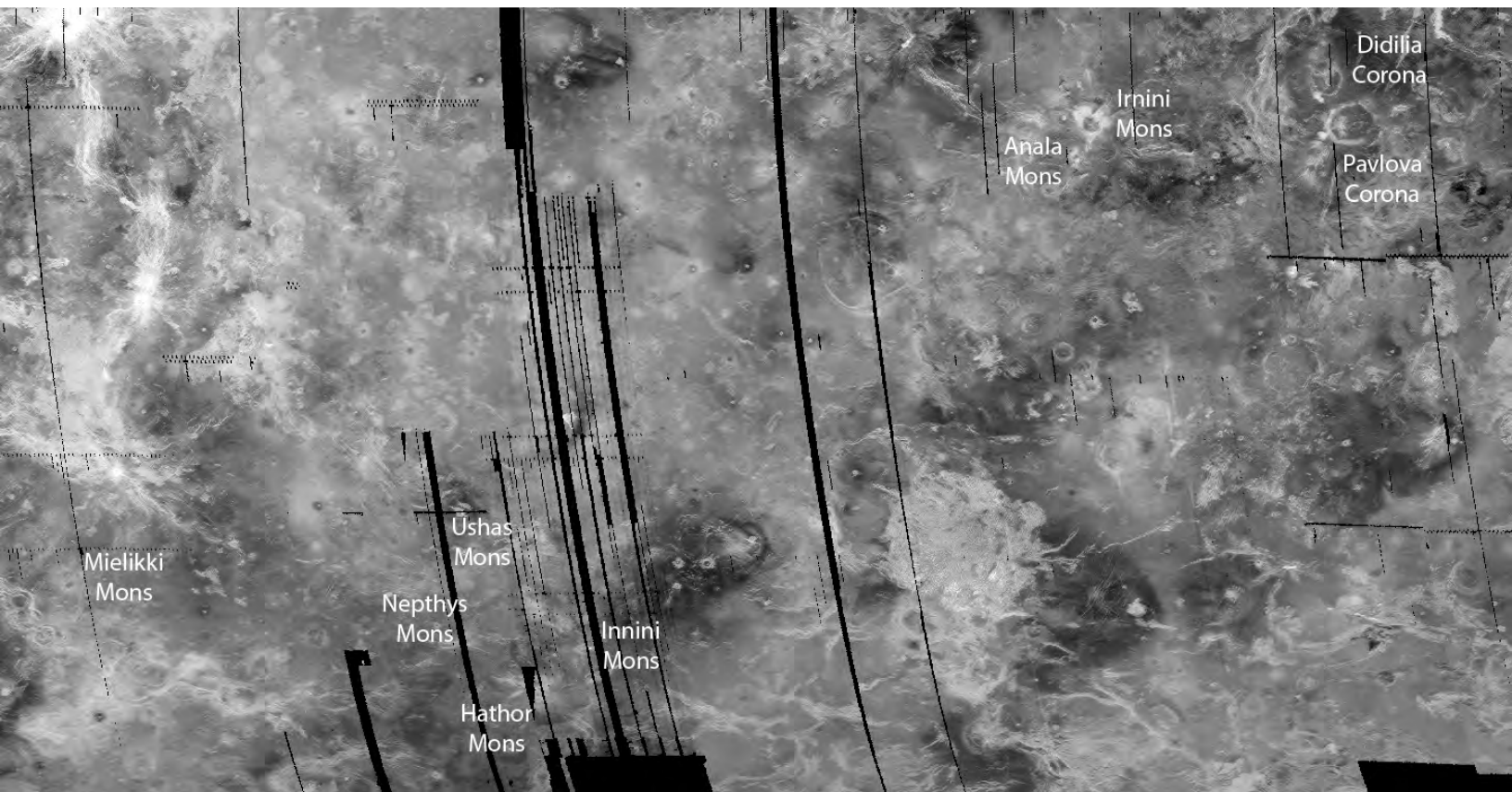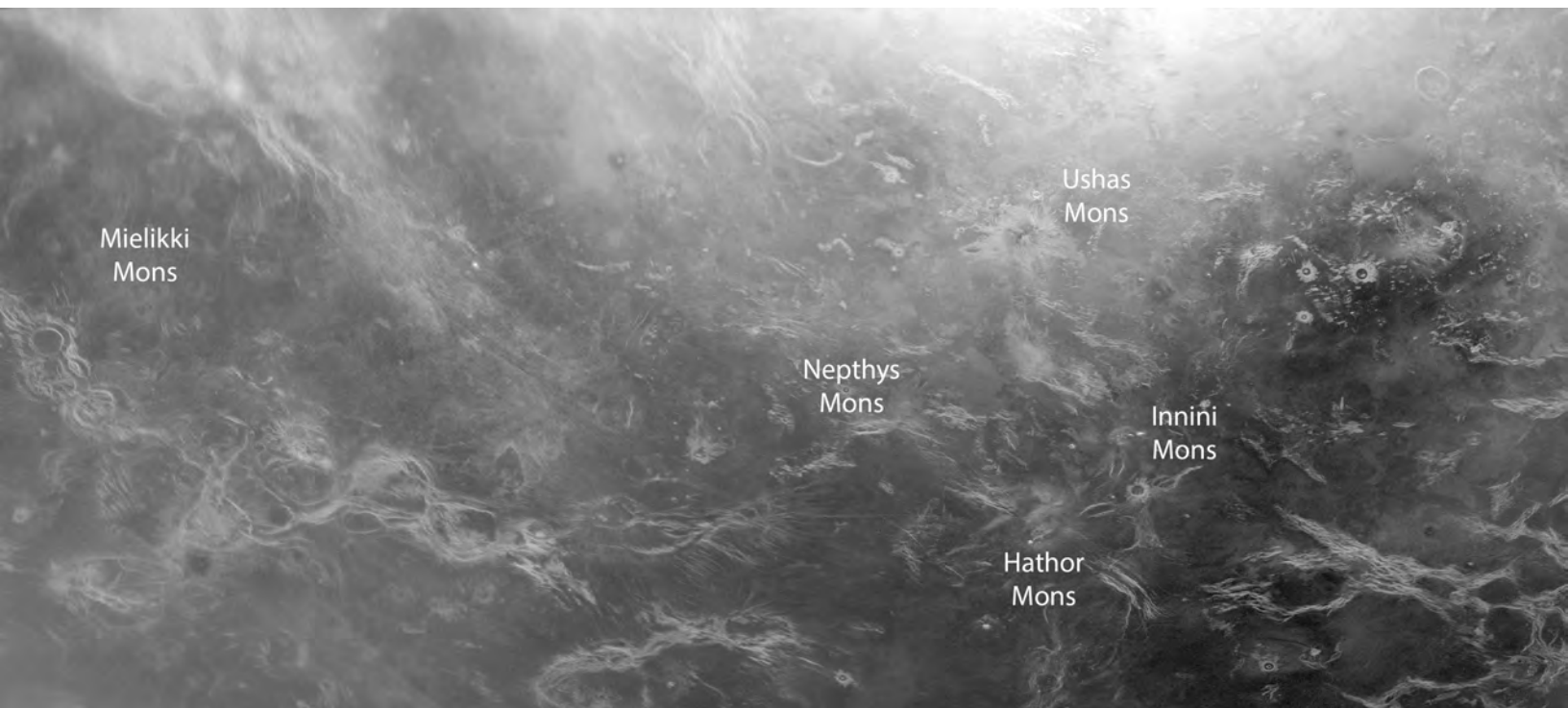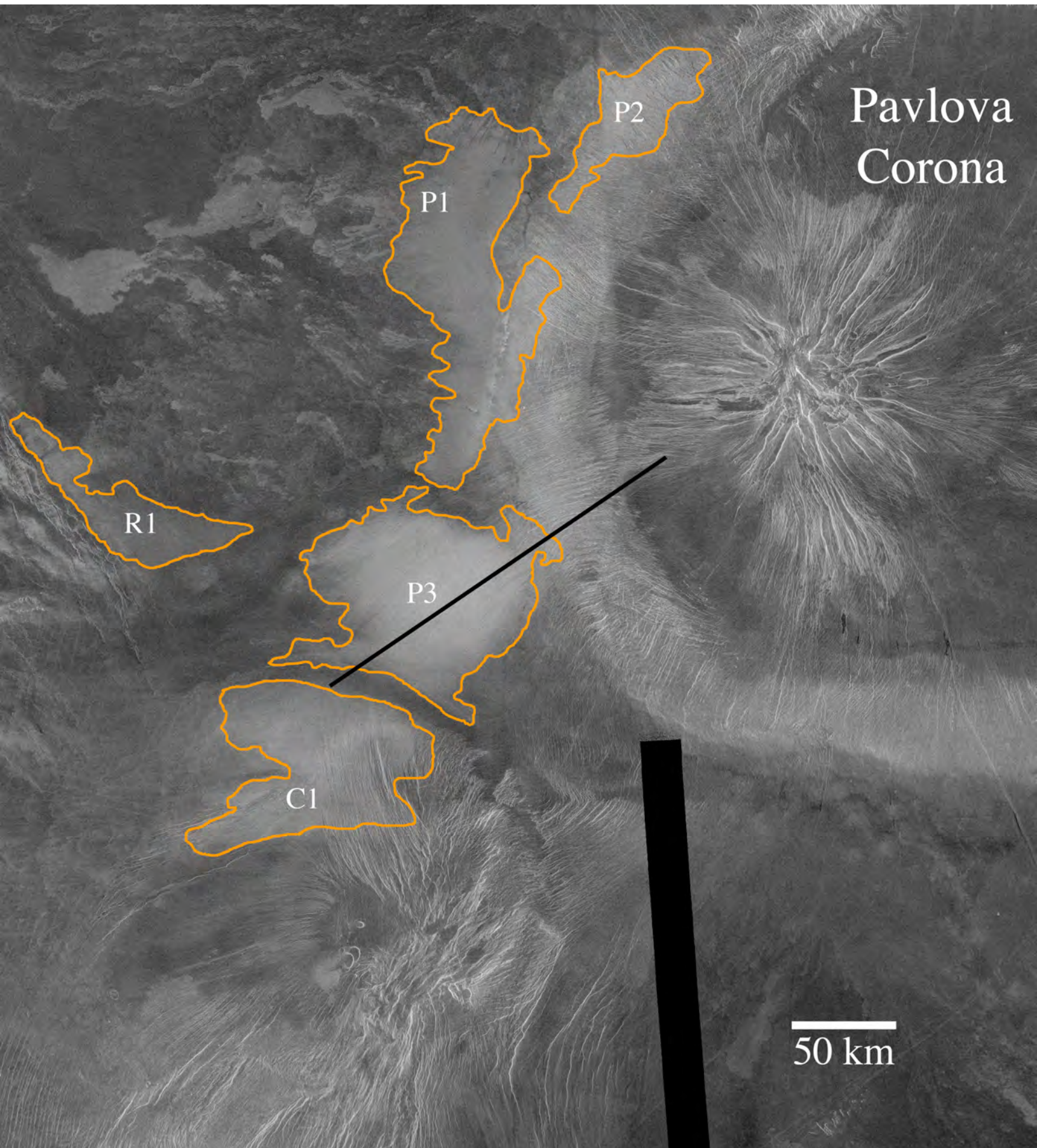
Figure 3.

Pavlova Corona

Figure 4.

Figure 5.

Didilia Corona

D1

50 km

P2

Figure 6.

Figure 7.

5 km

Figure 8.

I1

I3

Sappho
Patera

I2

Irnini Mons

A1

Anala Mons
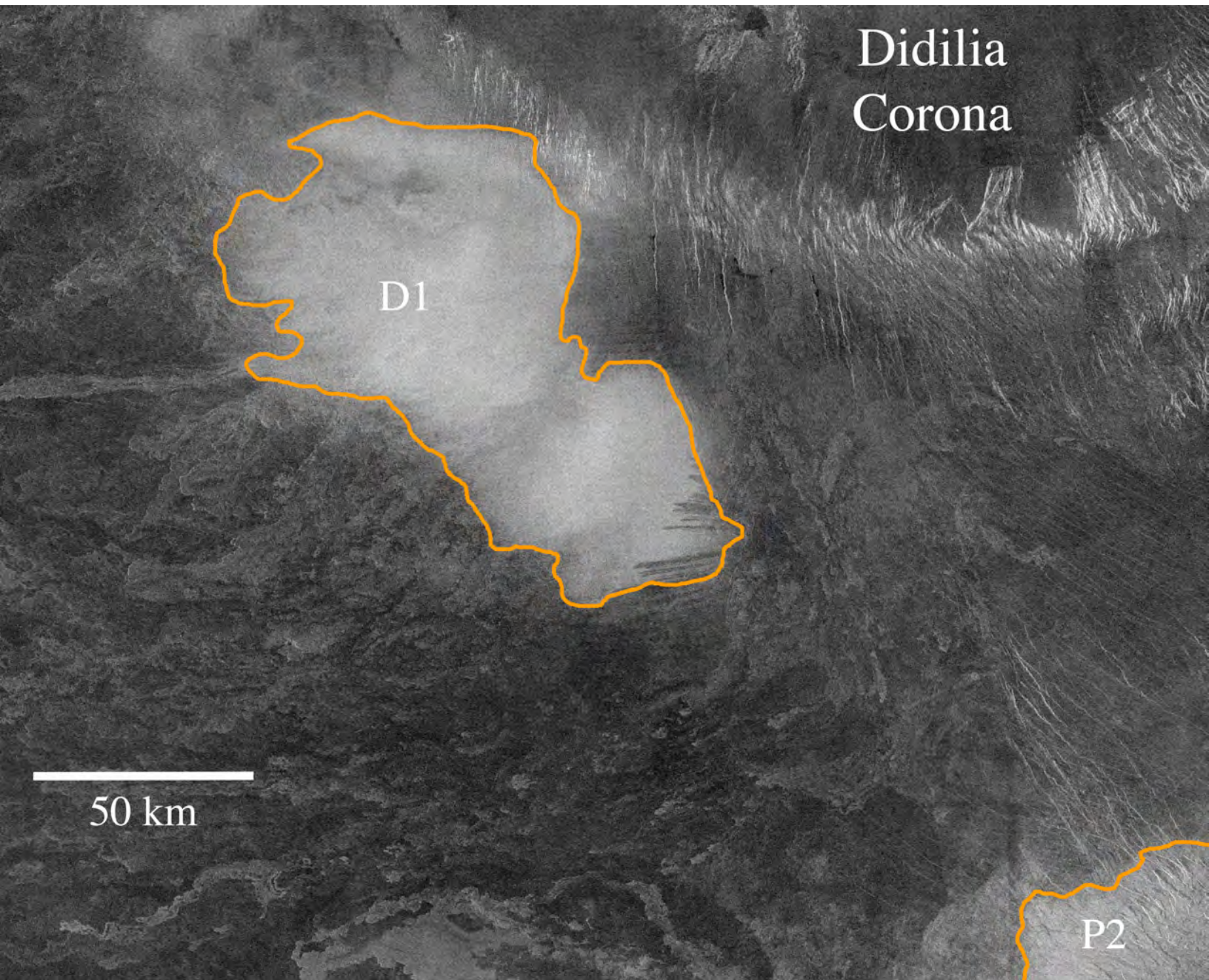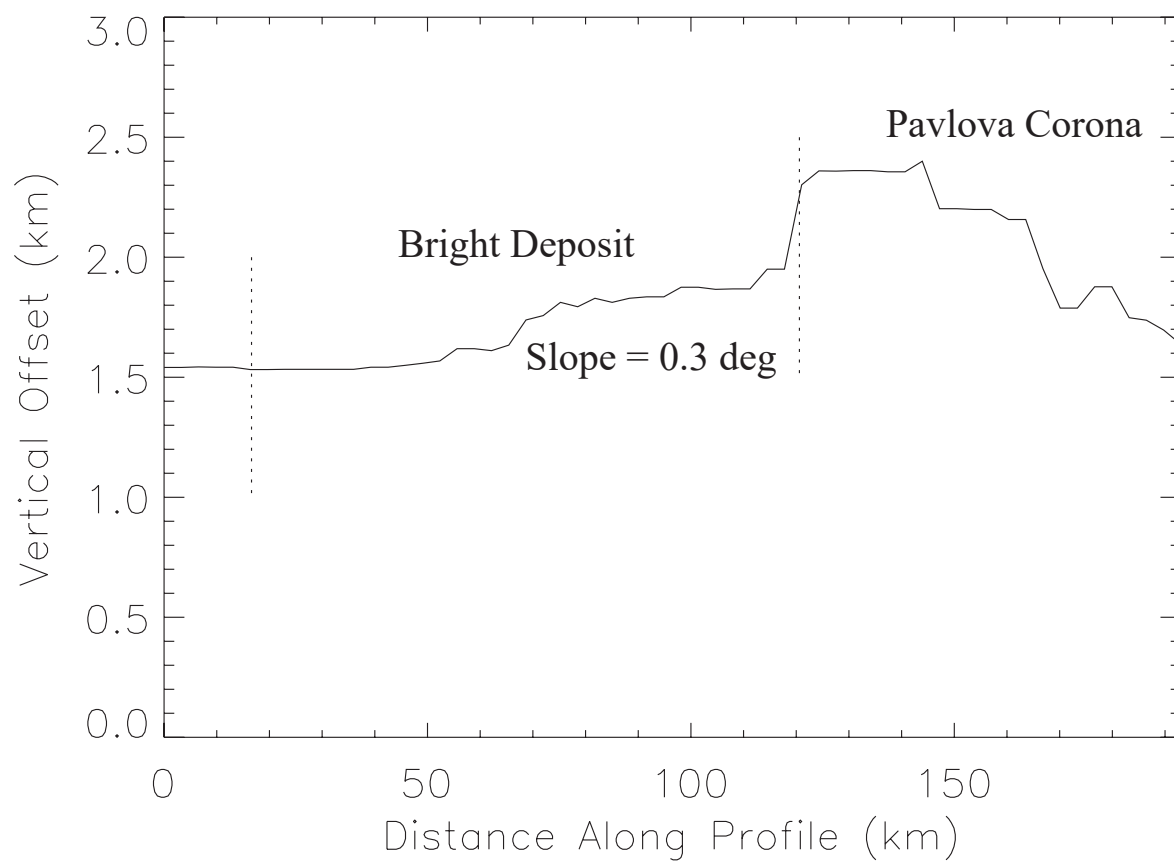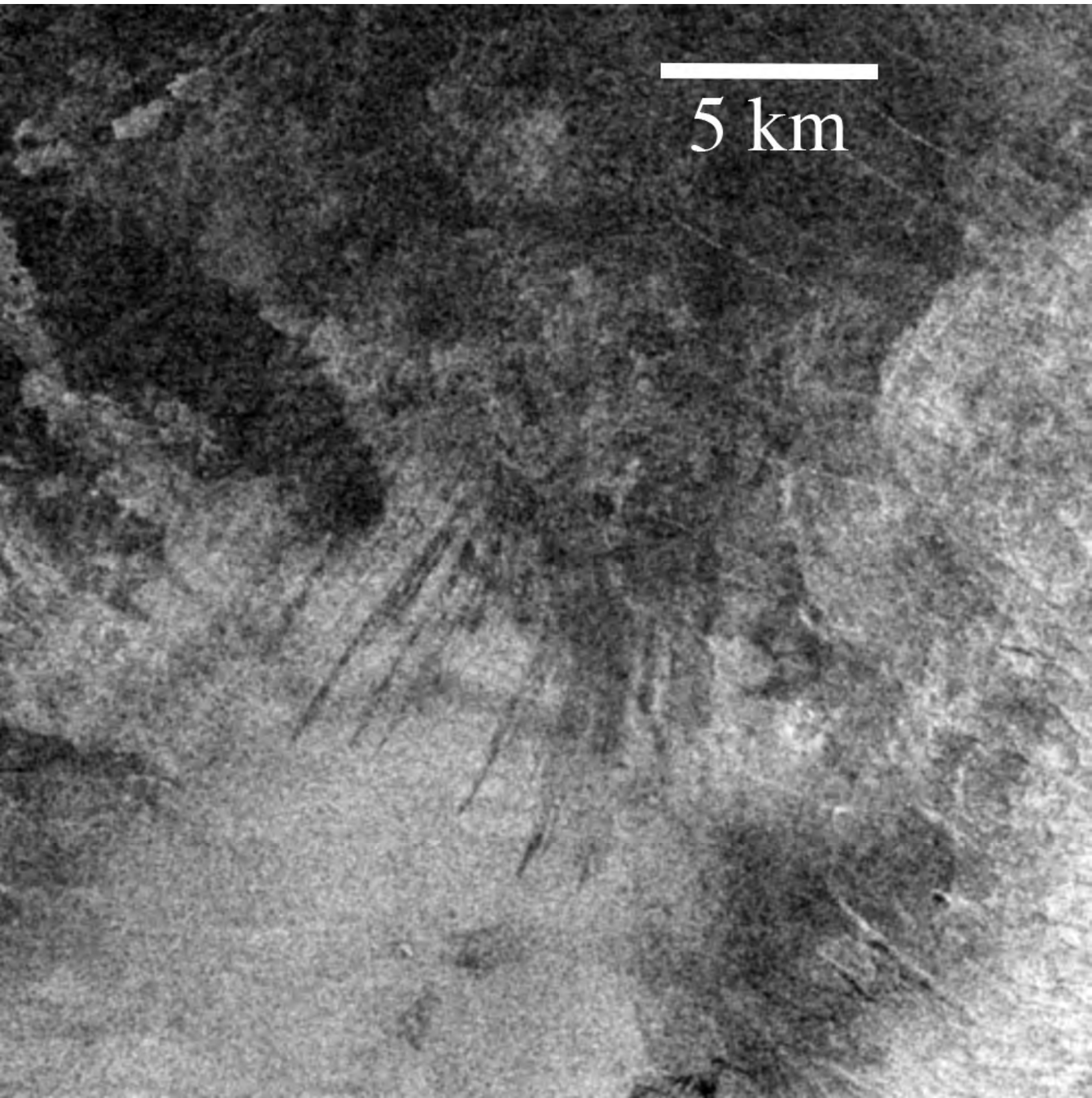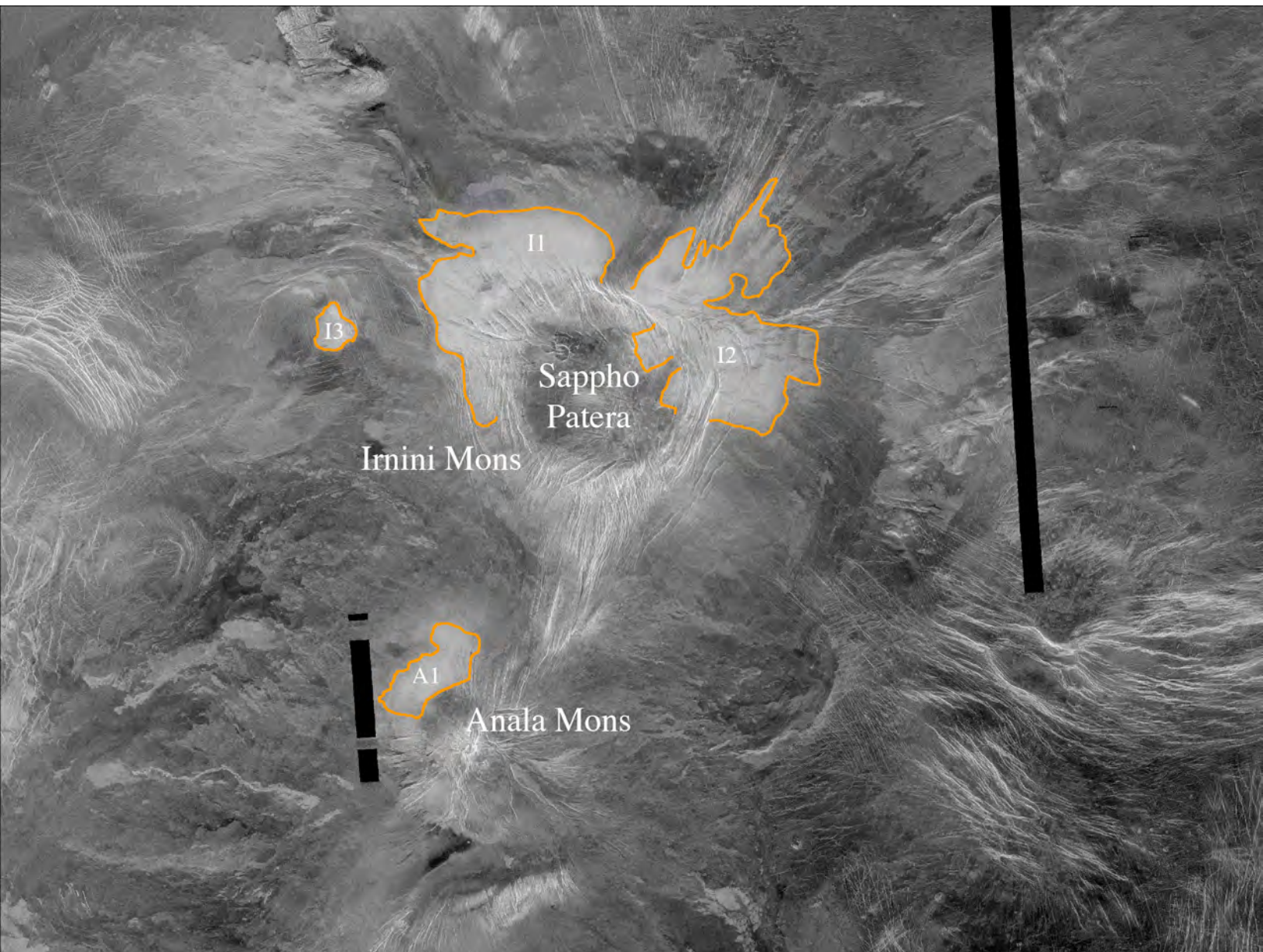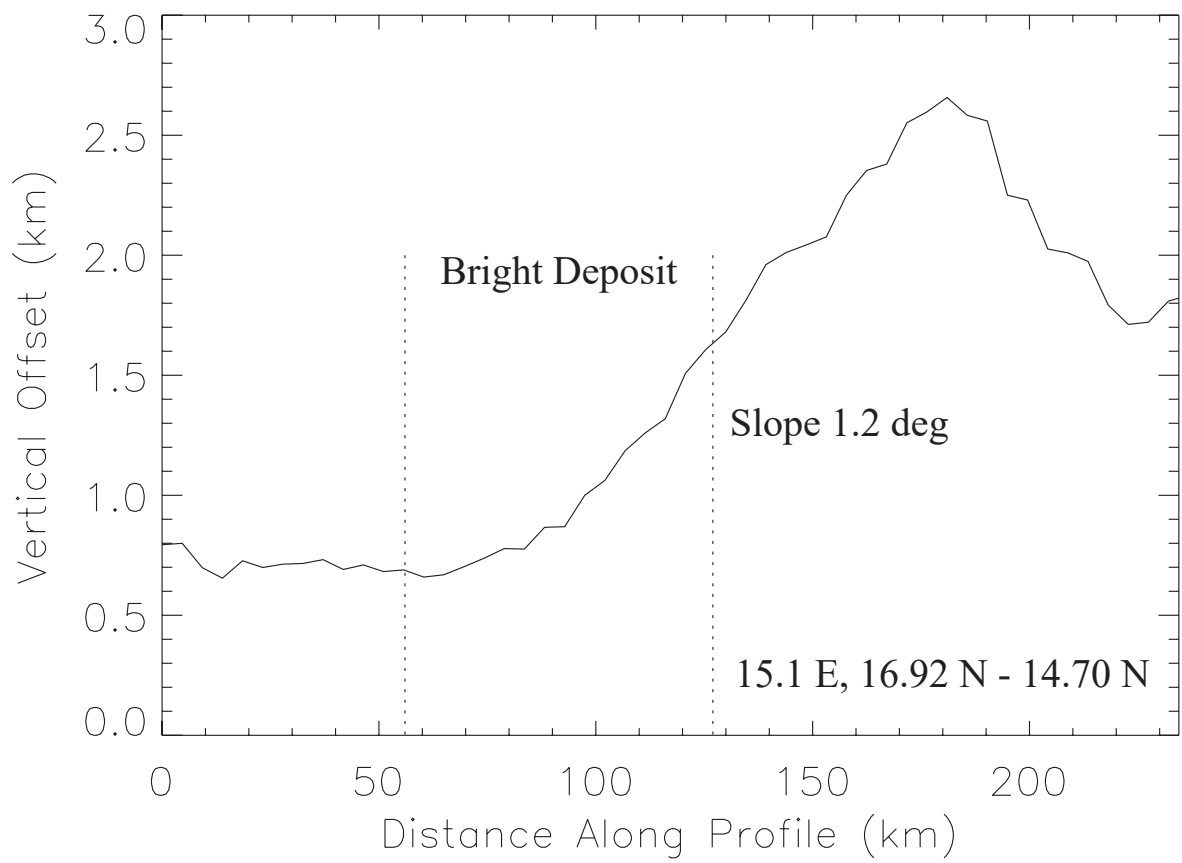
Figure 9.

Figure 10.

Figure 11.

Figure 12.

15 km

Figure 13.

a

Ushas
Mons

Nepthys
Mons

Innini
Mons

Hathor
Mons

b

Ushas
Mons

Nepthys
Mons

Innini
Mons

Hathor
Mons

CPR

0.5

0.0

Figure 14.

a

b
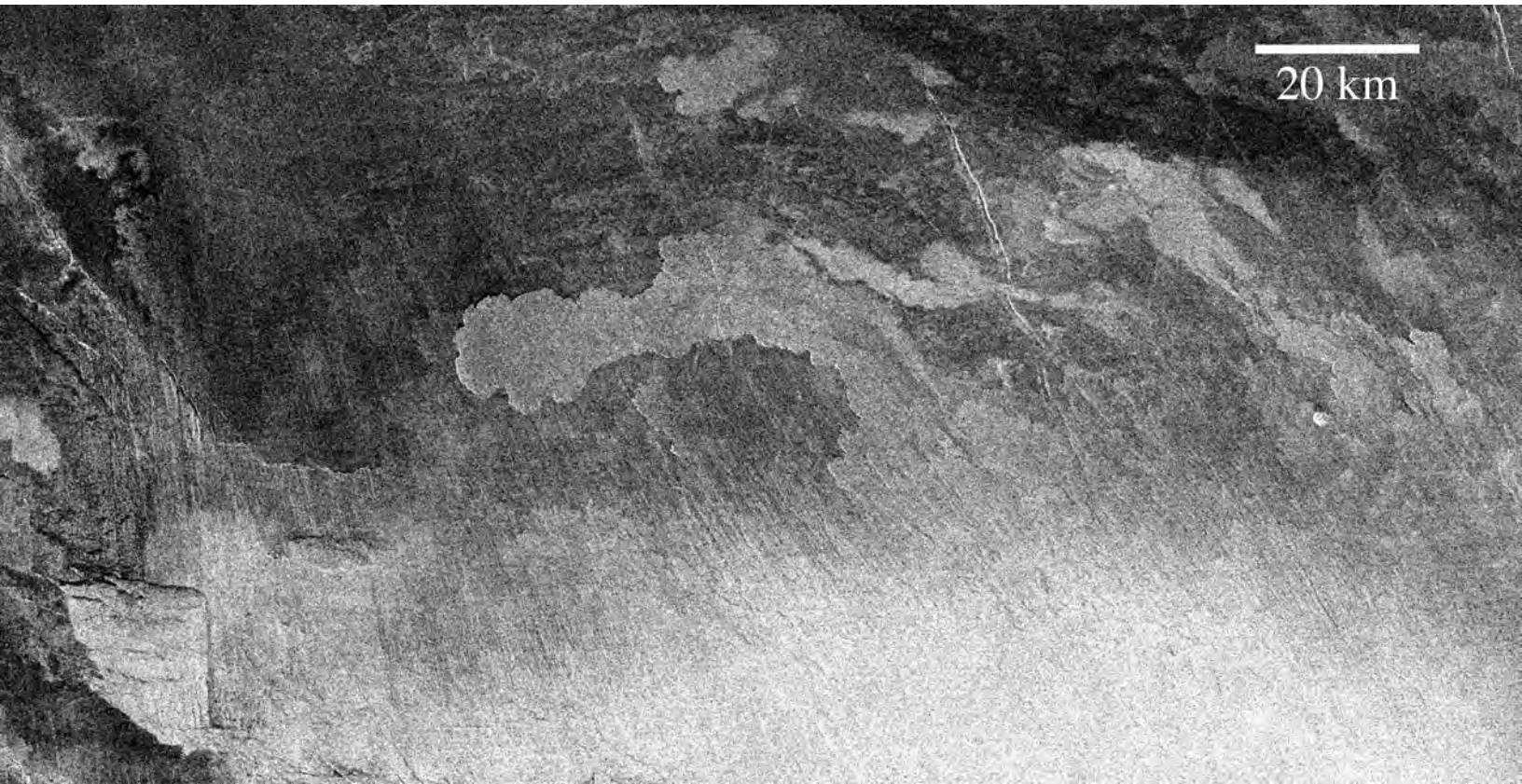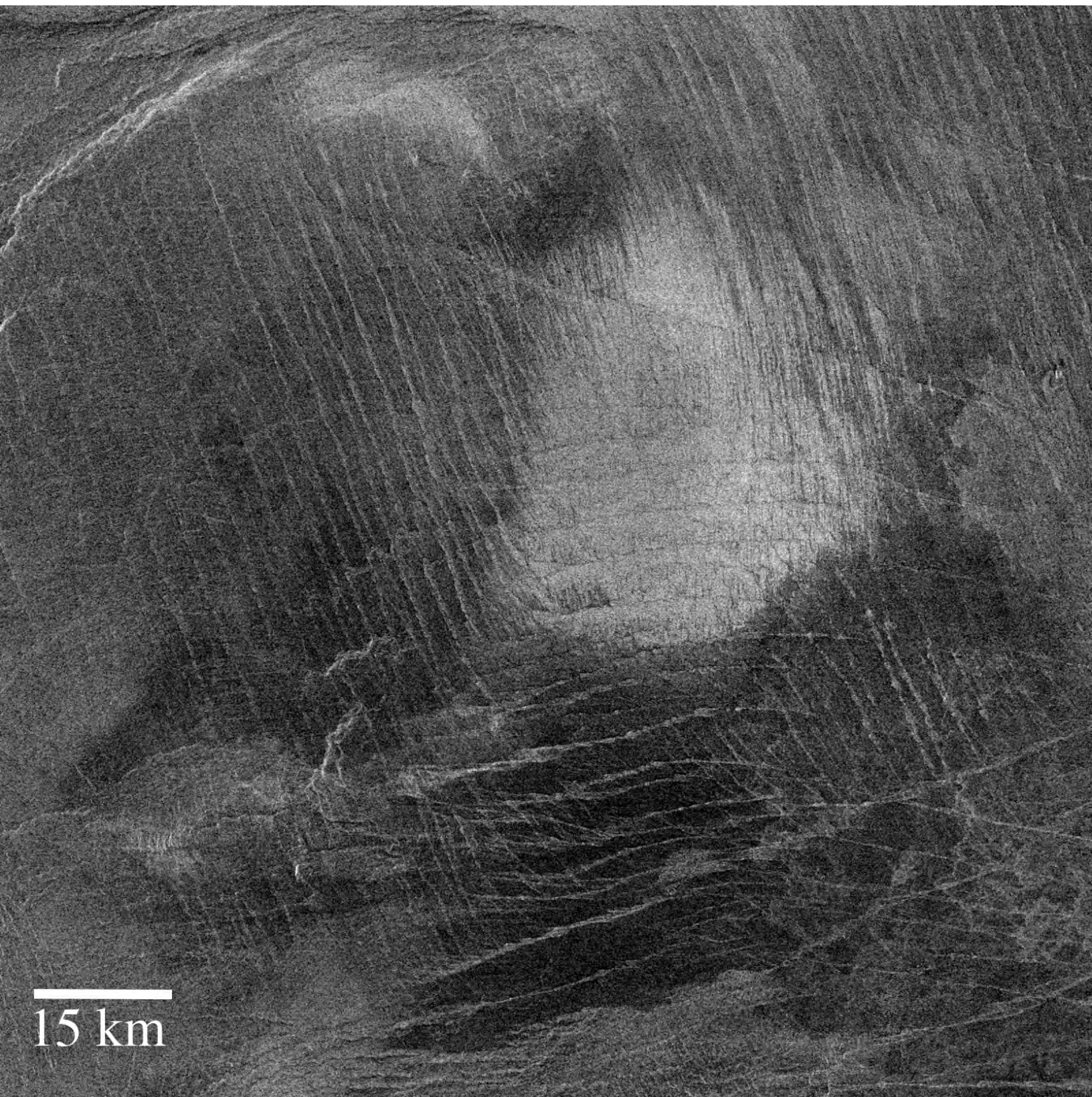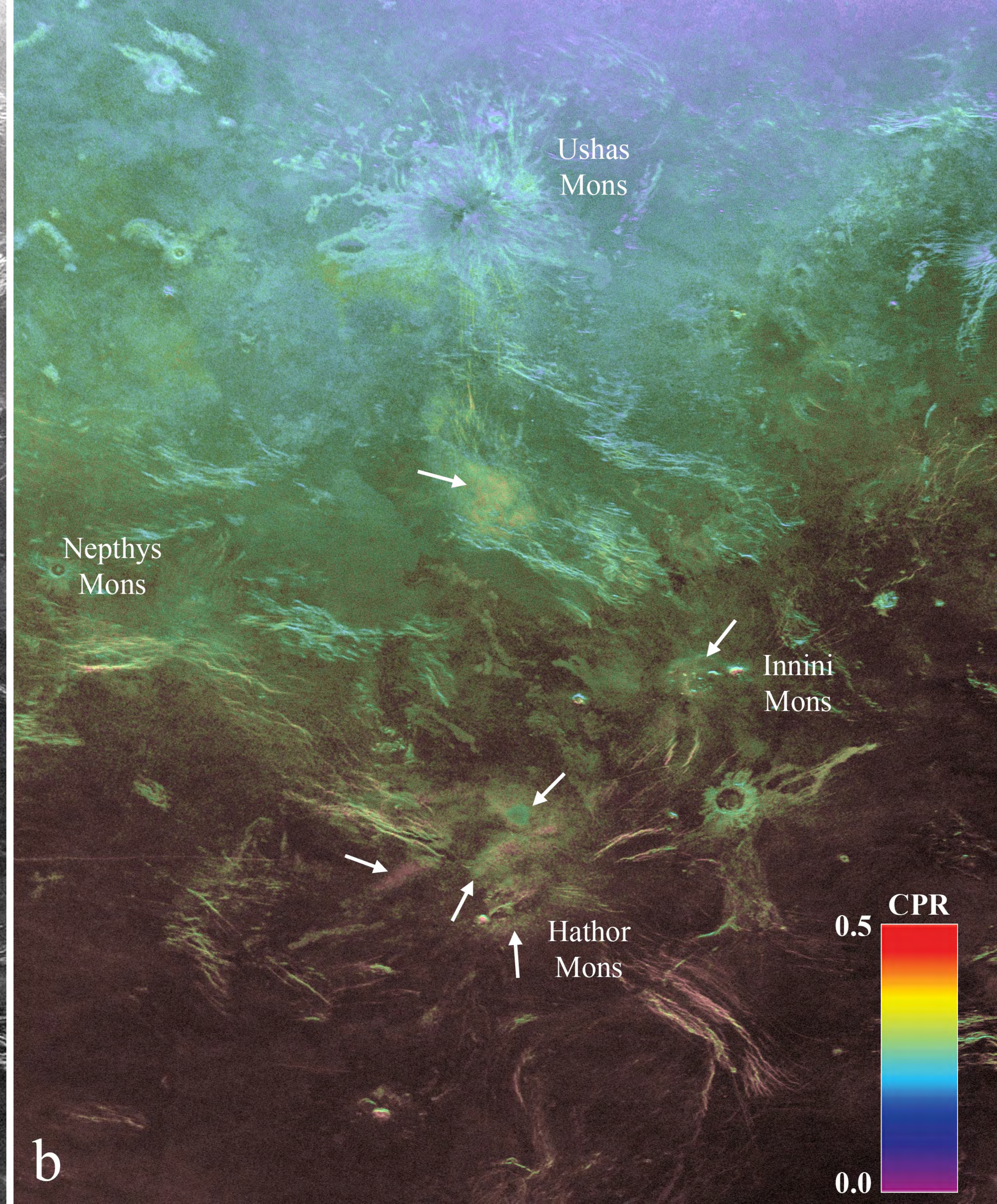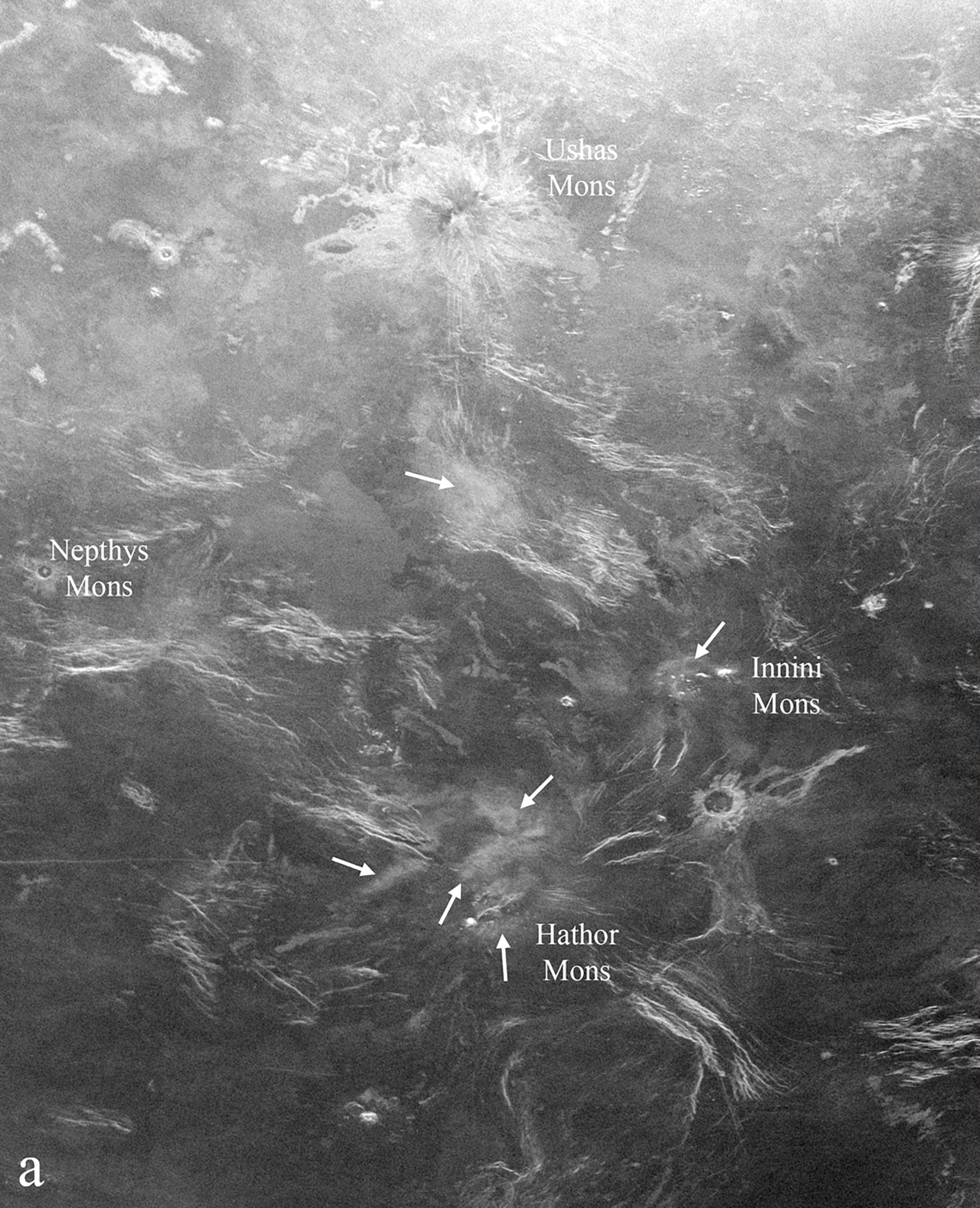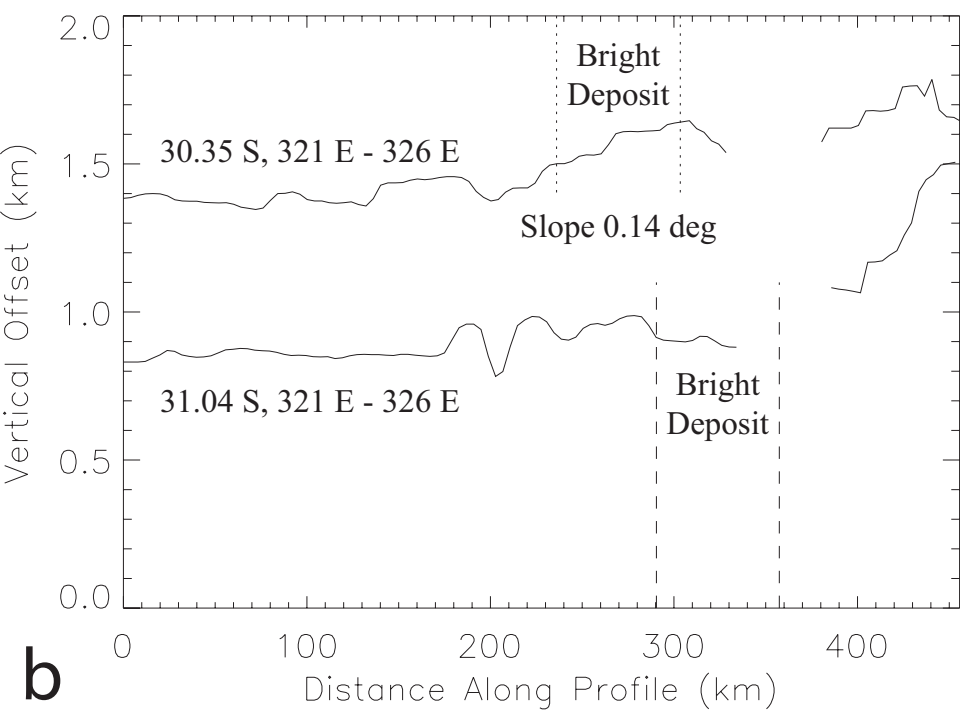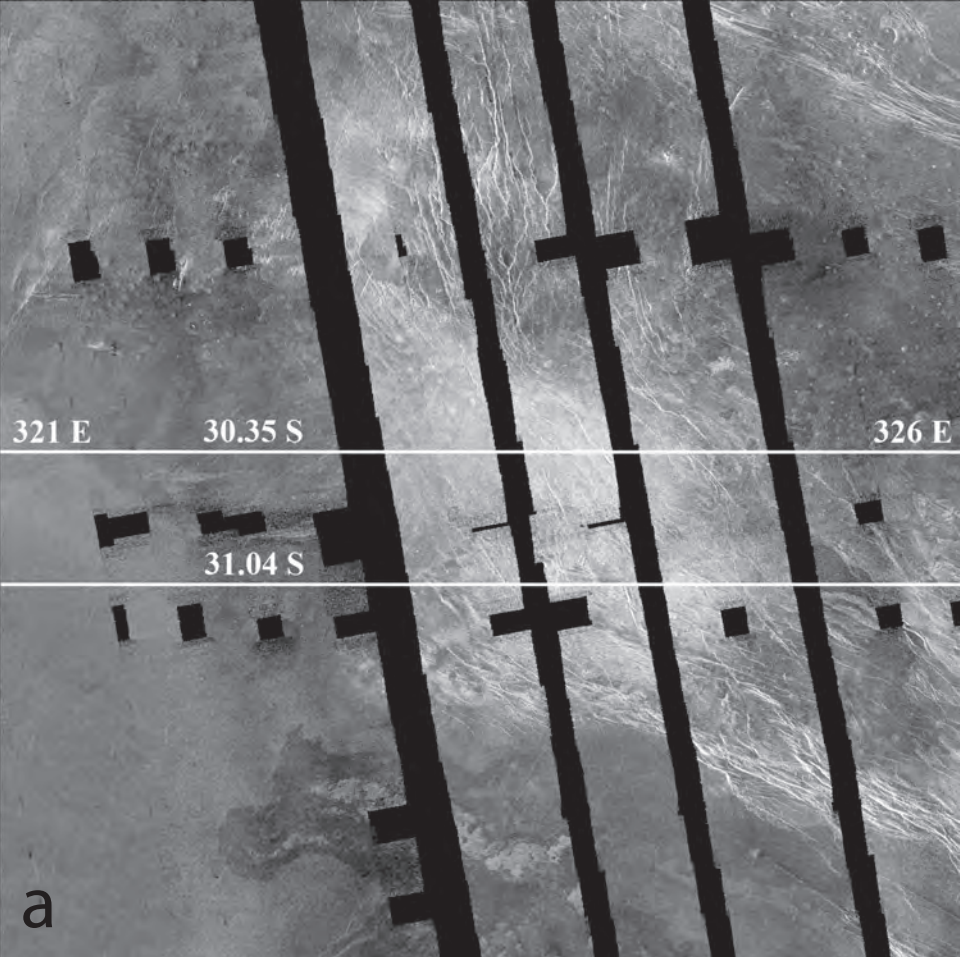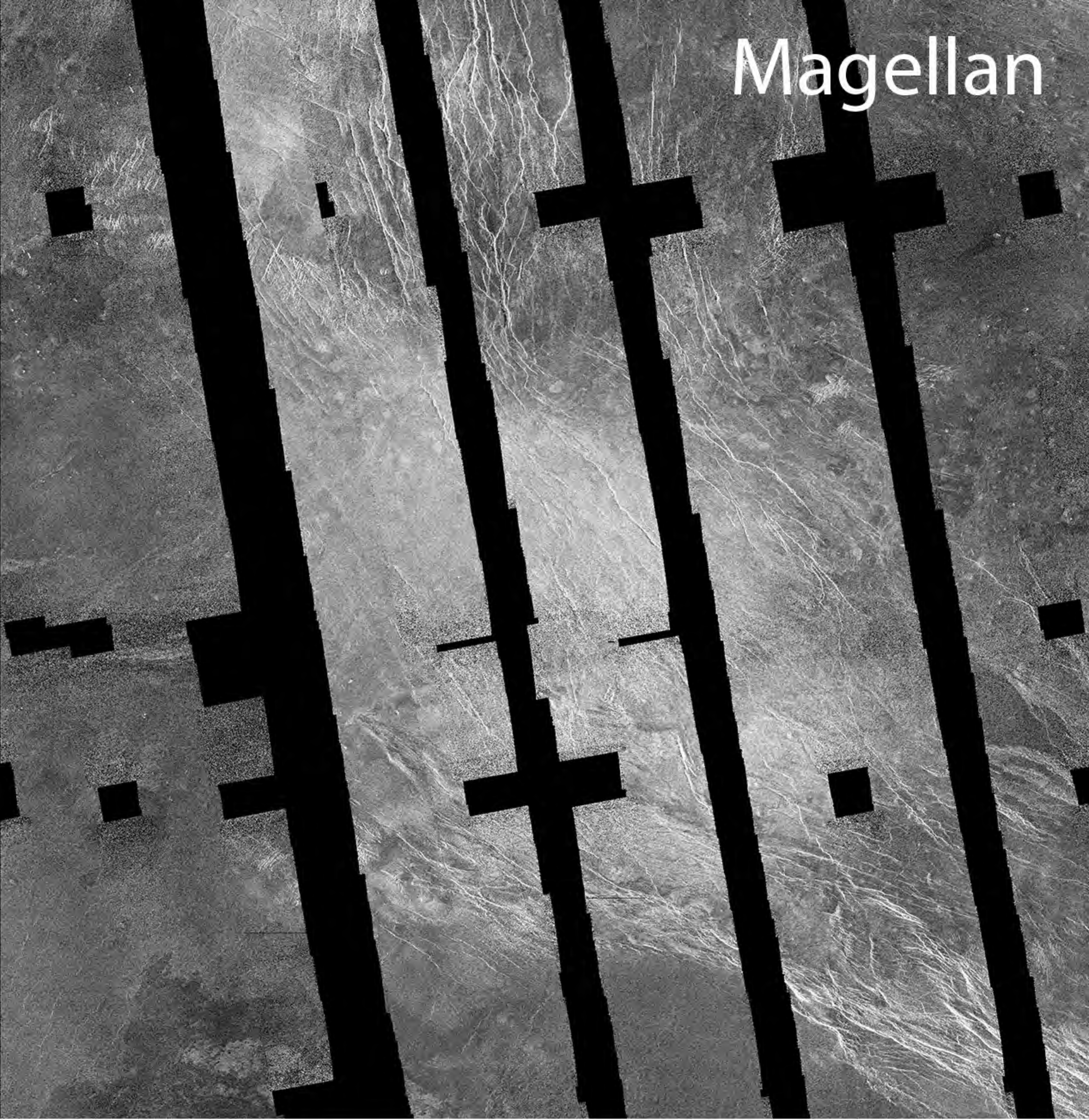
Figure 15.

Magellan

Earth-based SC
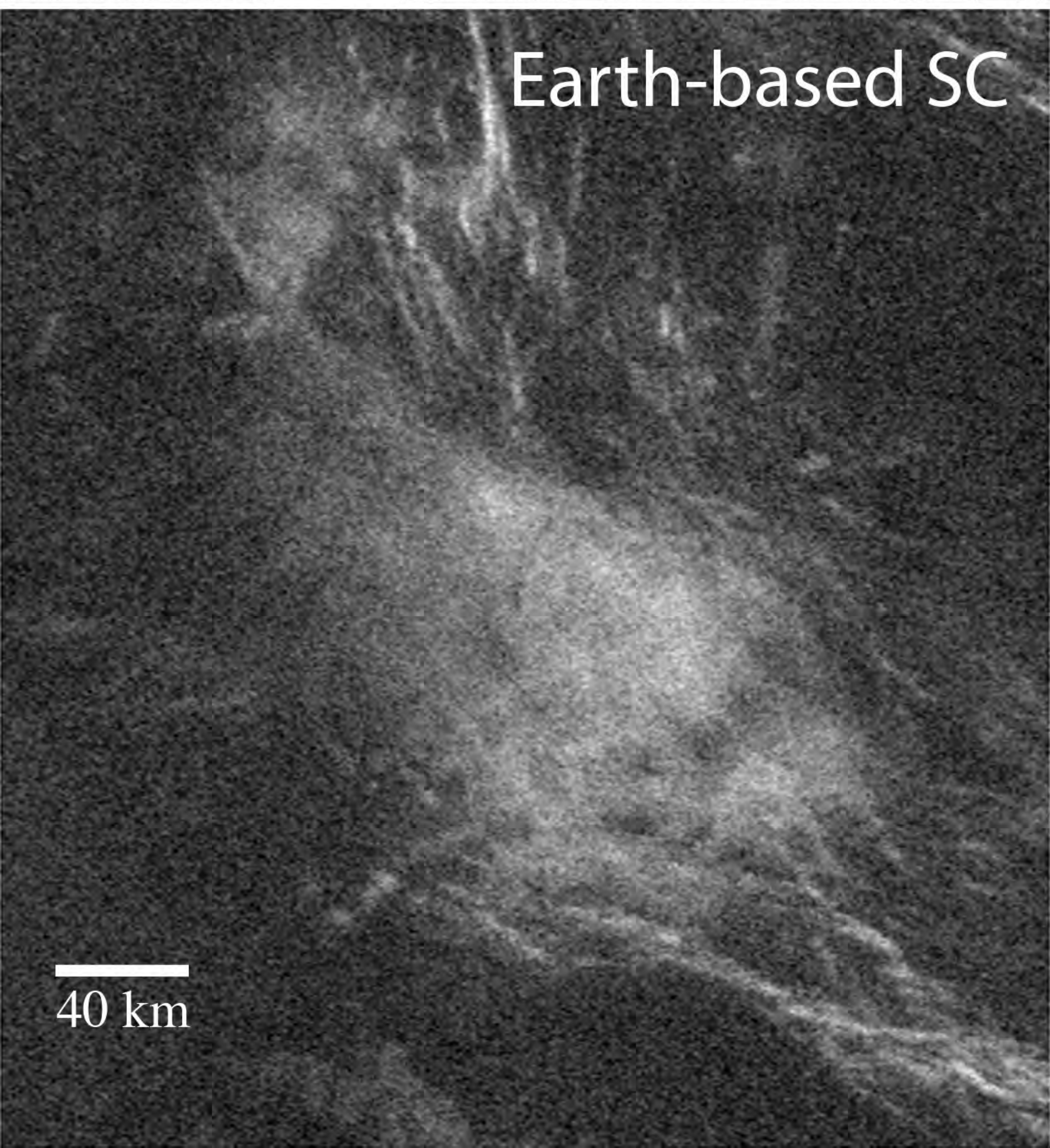
40 km

Figure 16.

Magellan
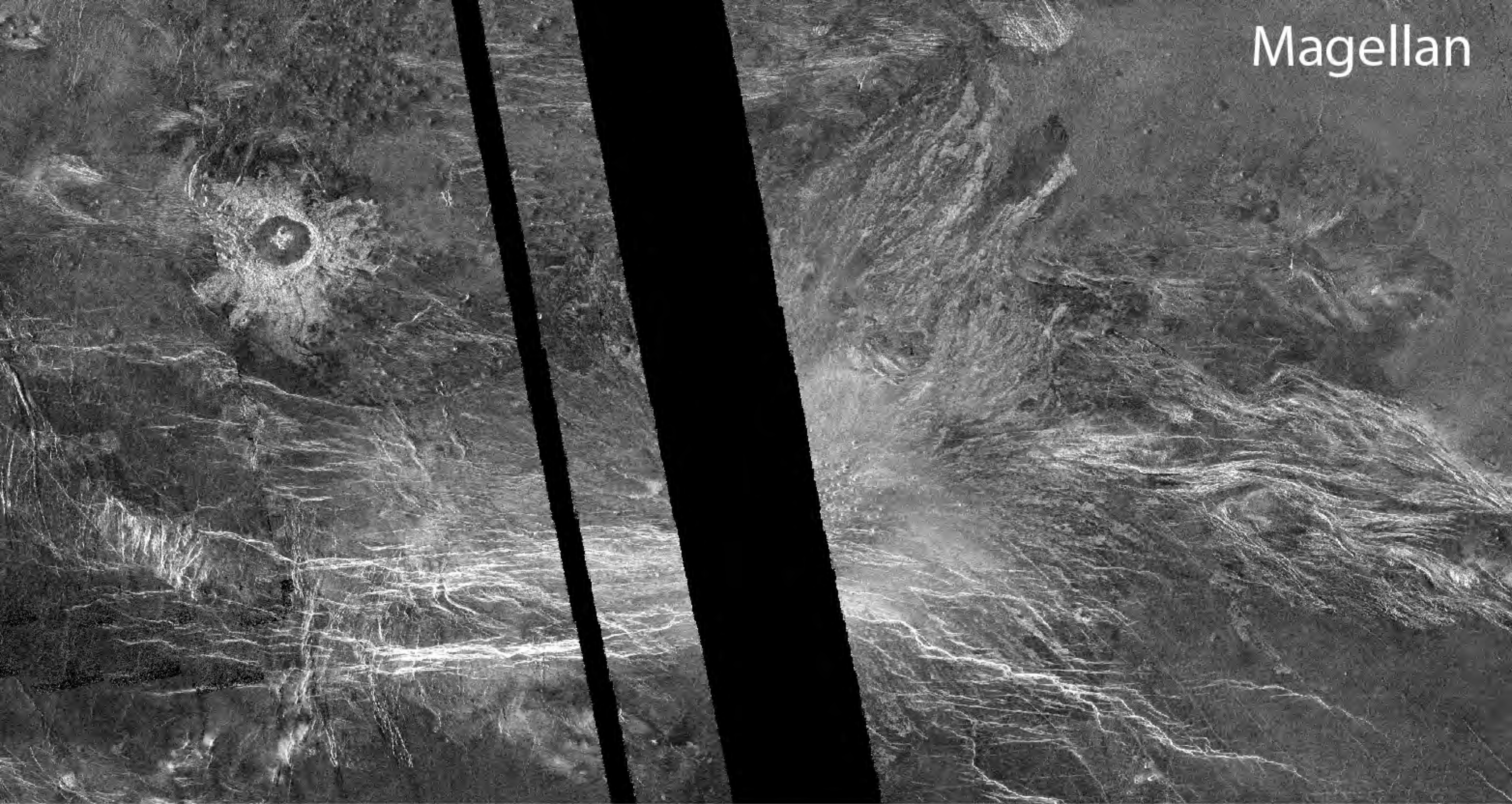
Earth-based SC
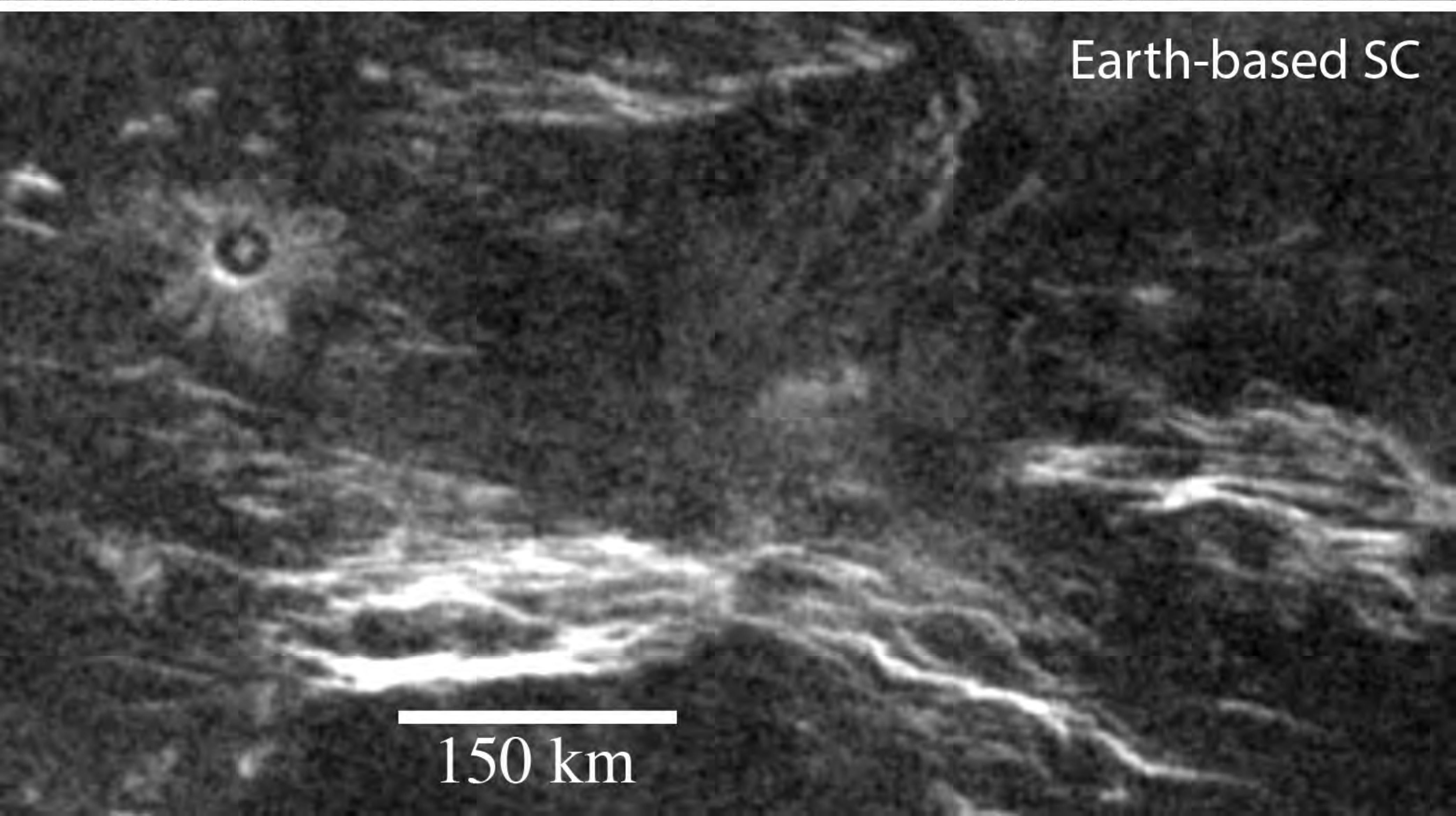
150 km

Figure 17.

Earth-based SC

80 km

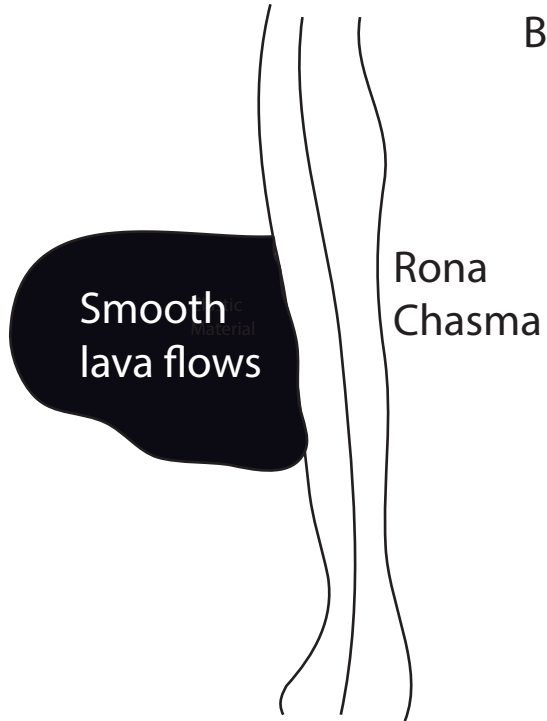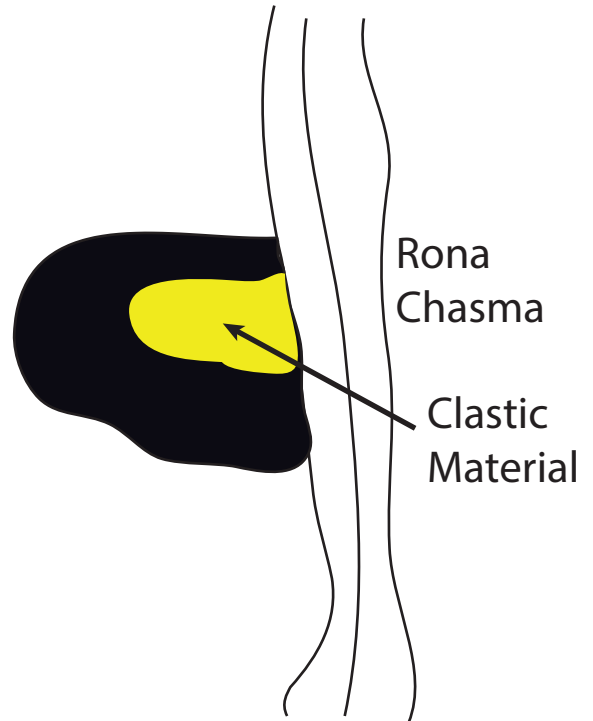**Figure 18.**
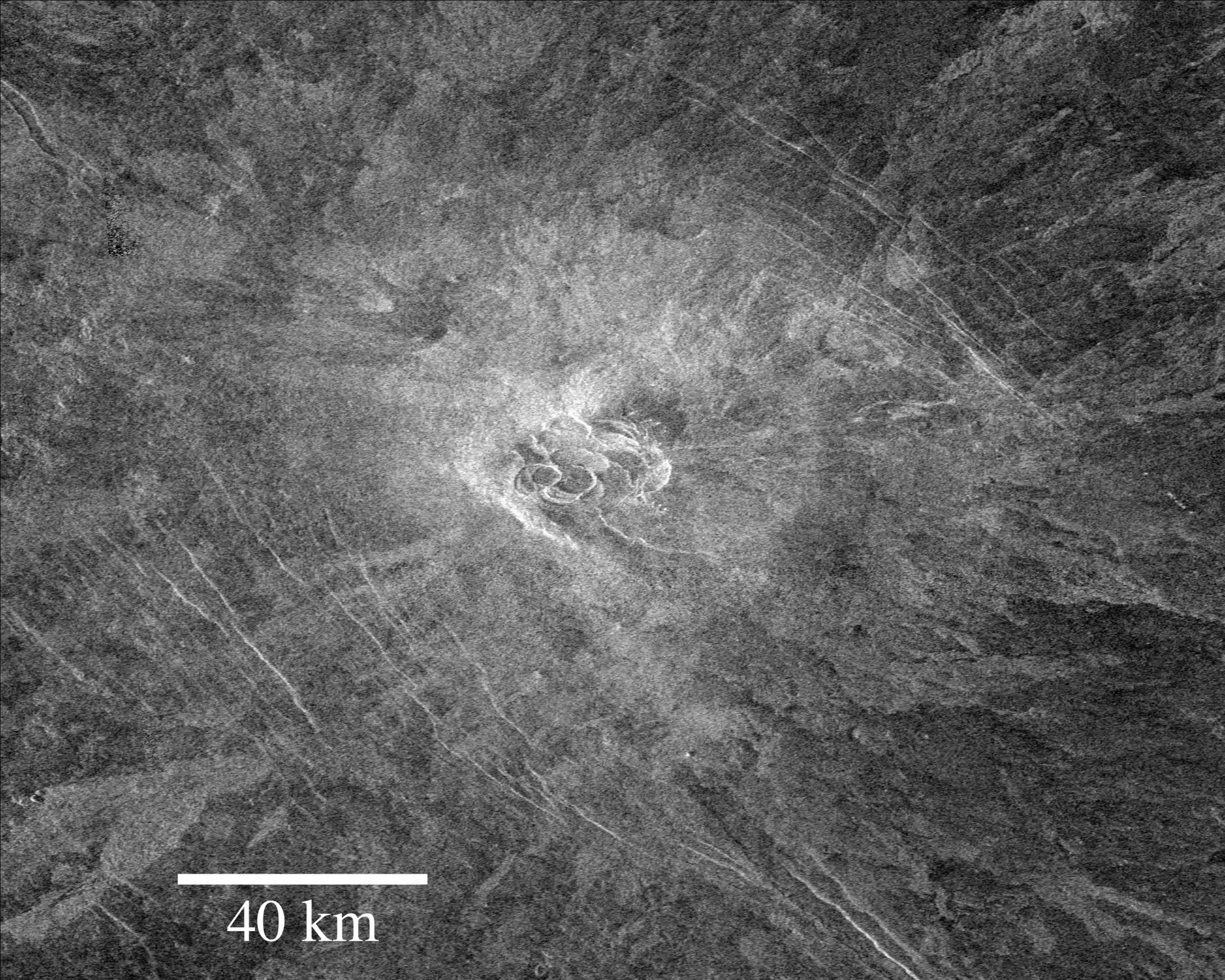
40 km

Figure 19.
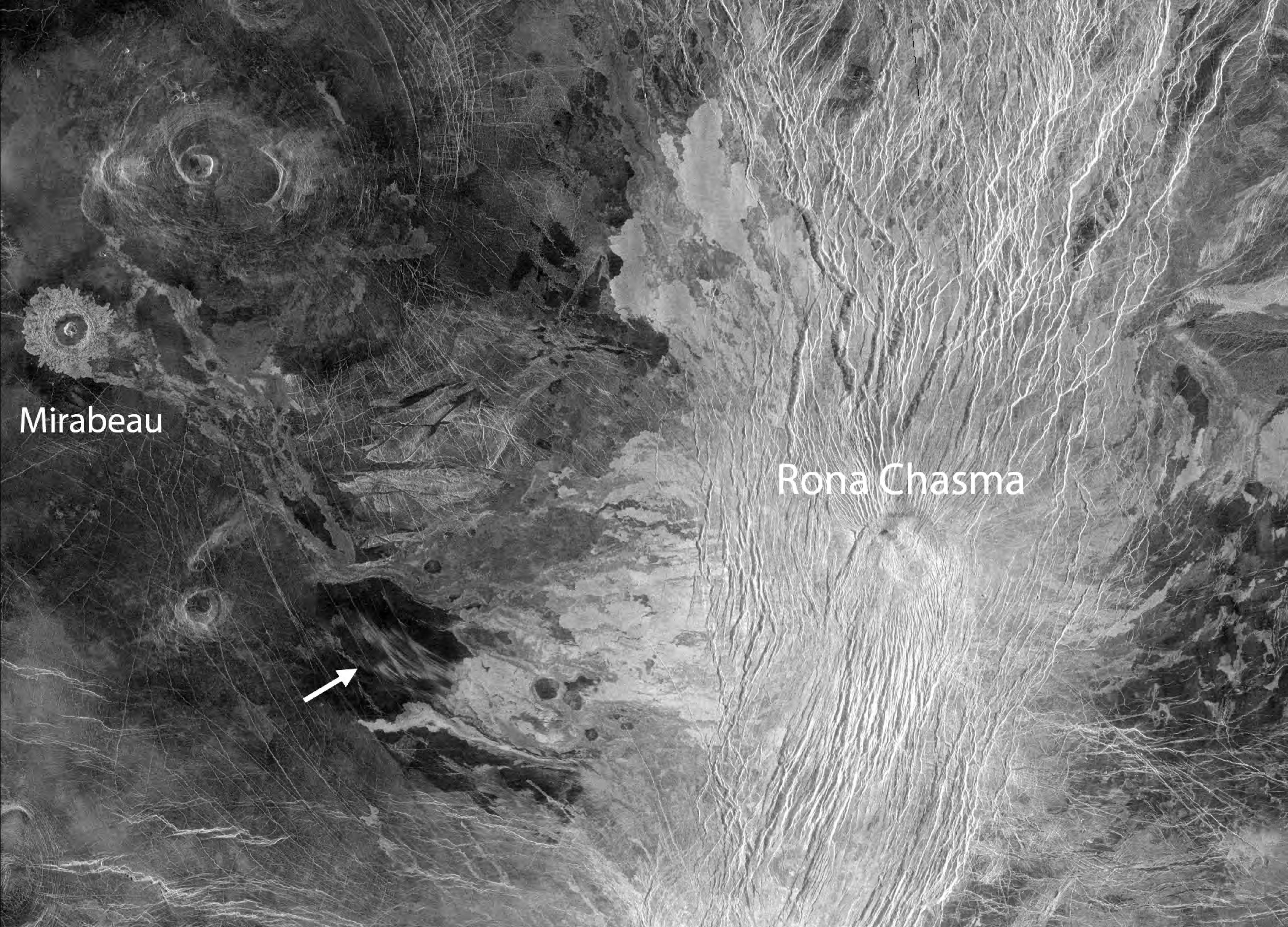
Mirabeau

Rona Chasma
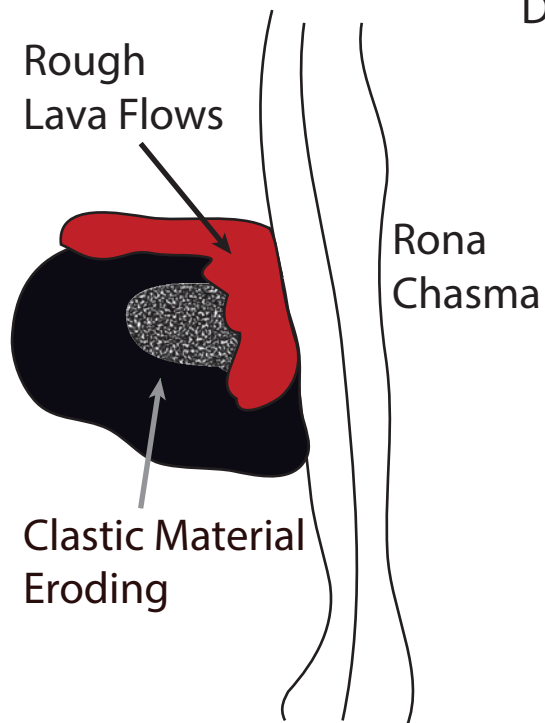
Figure 20.

40 km

Figure 21.

A. Smooth lava flows / Rona Chasma

B. Rona Chasma / Clastic Material

C. Rough Lava Flows / Rona Chasma / Clastic Material Eroding

D. Mirabeau Crater Forms / Rona Chasma / Clastic Material Streaks Form